Non-locality and destructive interference of matter waves

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- Neutrons: Wave-Particle Properties
- Coherence Properties
- Basics of Neutron Interferometry
- Dephasing - Decoherence
- Weak Measurements
- Active Neutron Apparatus Interaction (Fizeau)
- Résumé

The Neutron

Particle Properties

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

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

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

$\tau = 887(2)$ s

R = 0.7 fm

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

u - d - d - quark structure

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

CONNECTION

de Broglie

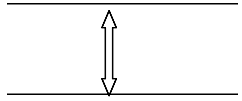
$$\lambda_B = \frac{h}{m.v}$$

Schrödinger

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

&

boundary conditions



Wave Properties

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

For thermal neutrons
= 1.8 Å, 2200 m/s

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

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

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

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

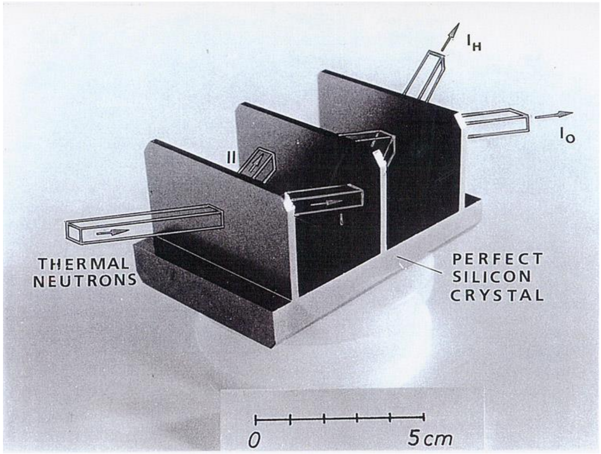
$$0 \leq \chi \leq 2\pi\ (4\pi)$$

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.

Neutron Interferometry

$$I_0 \;\propto\; \left|\psi_0{}^{I} + \psi_0{}^{II}\right|^2 \;\propto\; A + B\cos\chi$$

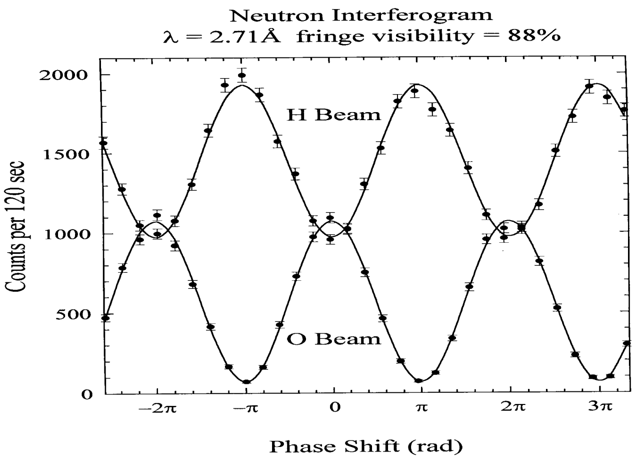
$$\chi = \oint \vec{k}\,d\vec{s} = (1-n)kD_{eff} \;\equiv\; -Nb_c\lambda D_{eff} = \Delta\cdot k = \Delta k\cdot D_{eff}$$



Self interference

(phase space density ~10^{-14})

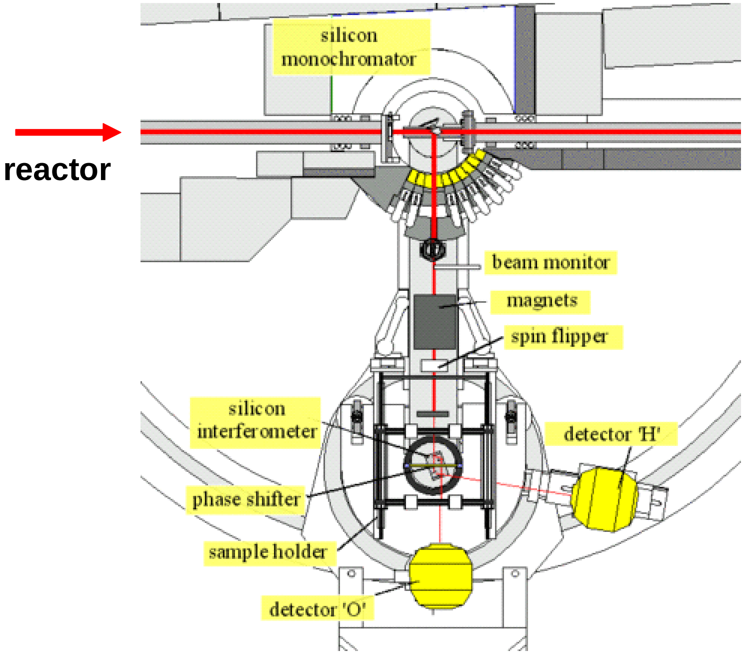
Efficiency of detectors, polarizers, flippers >99%

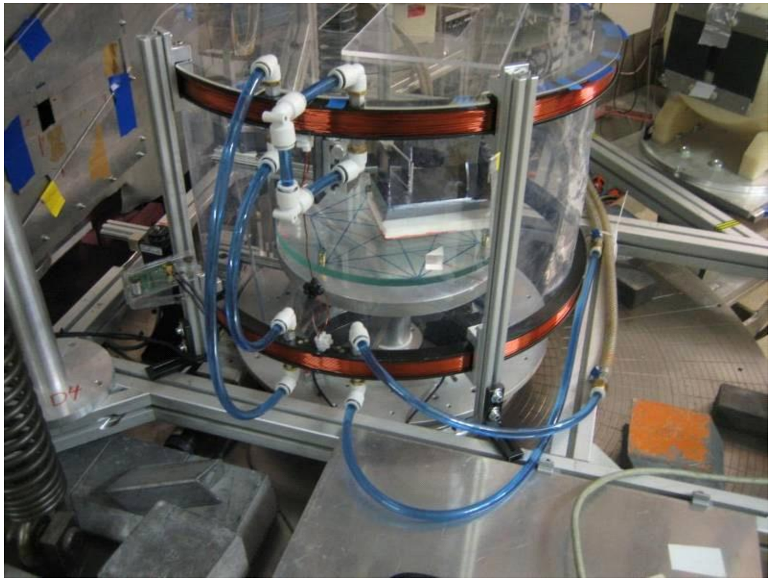


H. Rauch, W. Treimer, U. Bonse, Phys.Lett. A47 (1974) 369

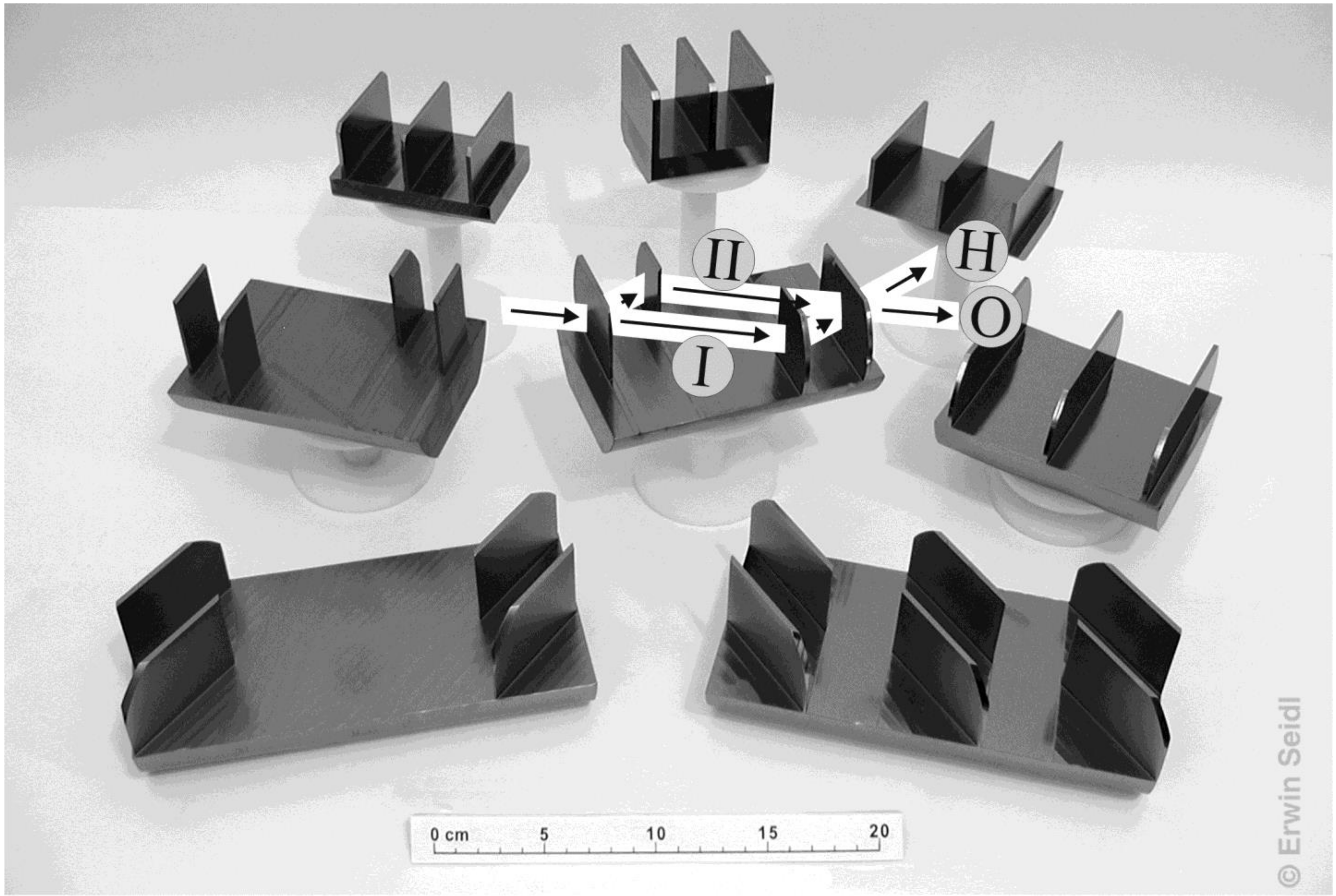
Interferometer set-up S18

Instutut Laue-Langevin, Grenoble



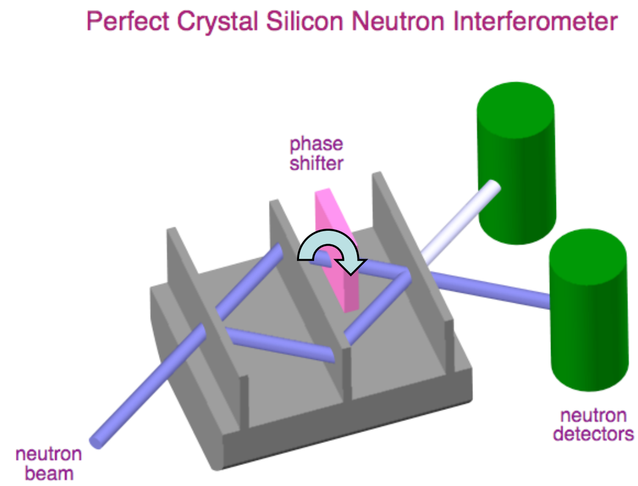


Interferometer family

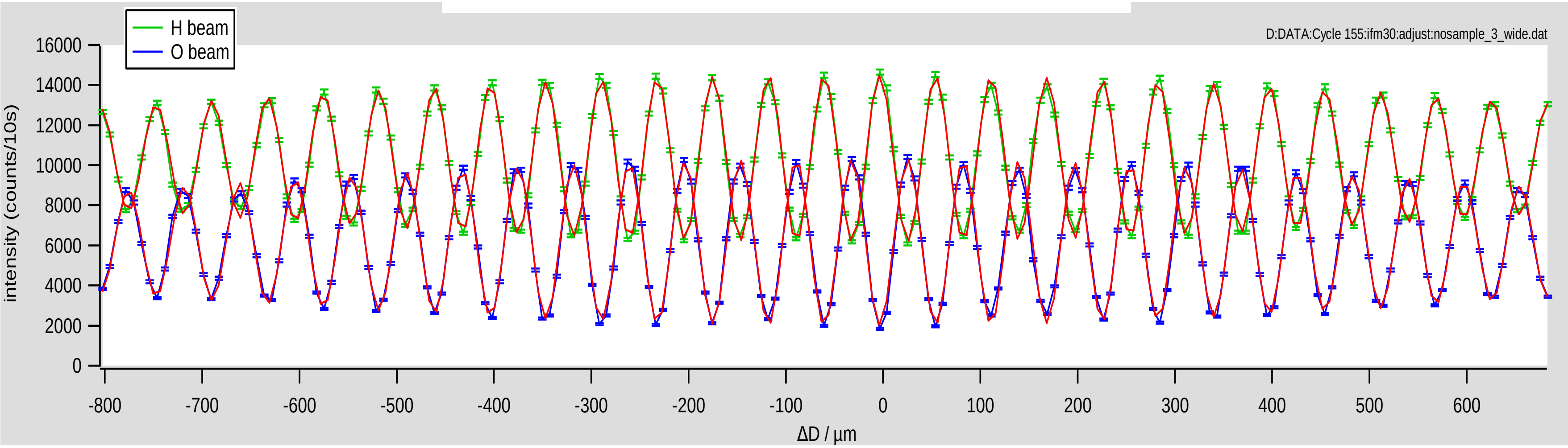


$I_0 = c|\, trr + rrt \,|^2$

High order interferences



λ = 1.92(2) Å



-30 -20 -10 0 10 20

Δ[Å]

State presentations

Schrödinger Equation:

$$-\frac{\hbar^2}{2m}\Delta\psi(\vec{r},t) + V(\vec{r},t)\psi(\vec{r},t) = i\hbar\frac{\partial\psi(\vec{r},t)}{\partial t}$$

Partial waves fill the whole space

Wave Function (Eigenvalue solution in free space):

$$\Psi(\vec{r},t) = (2\pi)^{-3/2}\int\psi(\vec{k},t)e^{i(\vec{k}\cdot\vec{r}-\omega t)}d^3\vec{k}$$

and others (Wigner function etc.)

Spatial distribution:

$$\rho(\vec{r},t) = |\psi(\vec{r},t)|^2$$

Momentum distribution:

$$g(\vec{k},t) = |\psi(\vec{k},t)|^2$$

Coherence Function:

Stationary situation: $(\tau = 0)$:

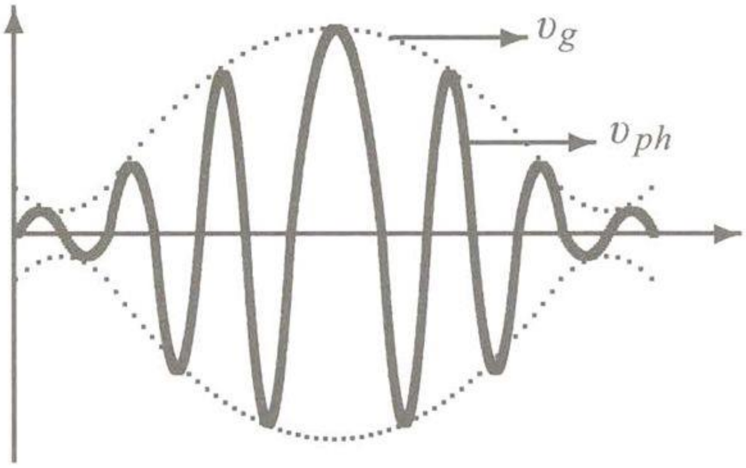
$$\tau = t - t'$$

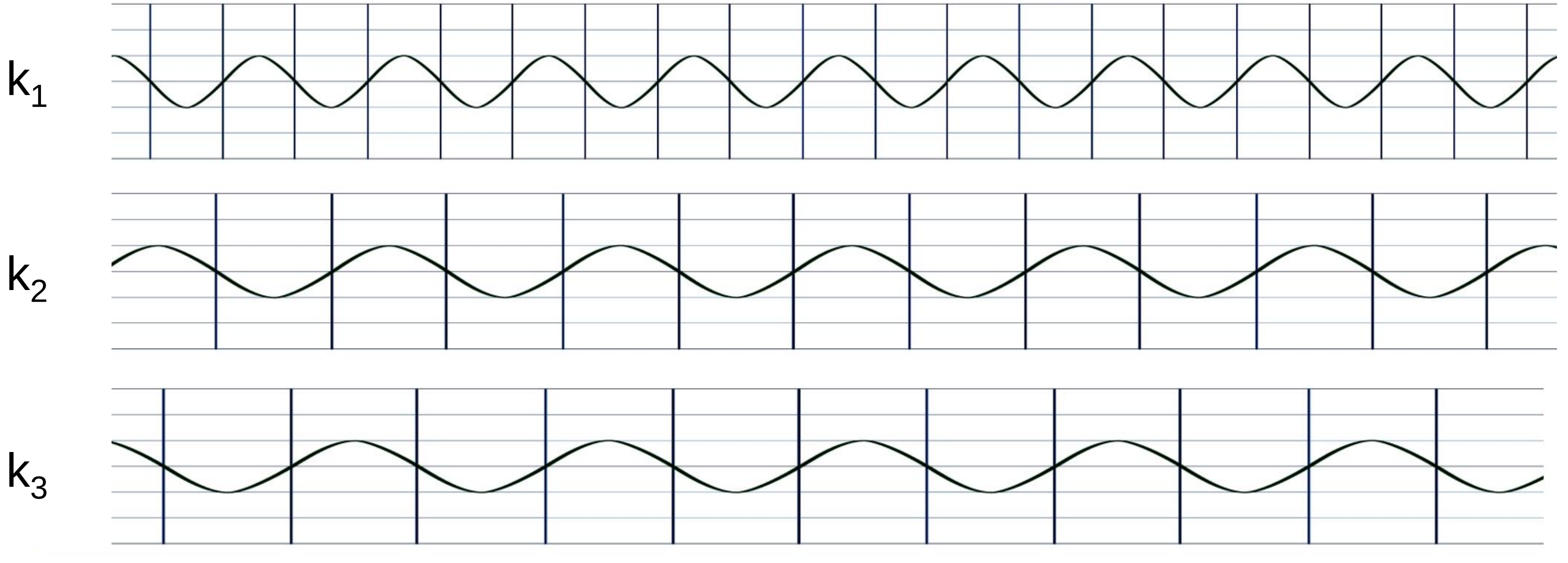
$$\vec{\Delta} = \vec{r} - \vec{r}';$$

$$\Gamma(\vec{\Delta}) = <\psi(0)\,\psi(\vec{\Delta})> = (2\pi)^{3/2}\int g(\vec{k})e^{i\vec{k}\vec{r}}d^3k$$

Wave-Packet

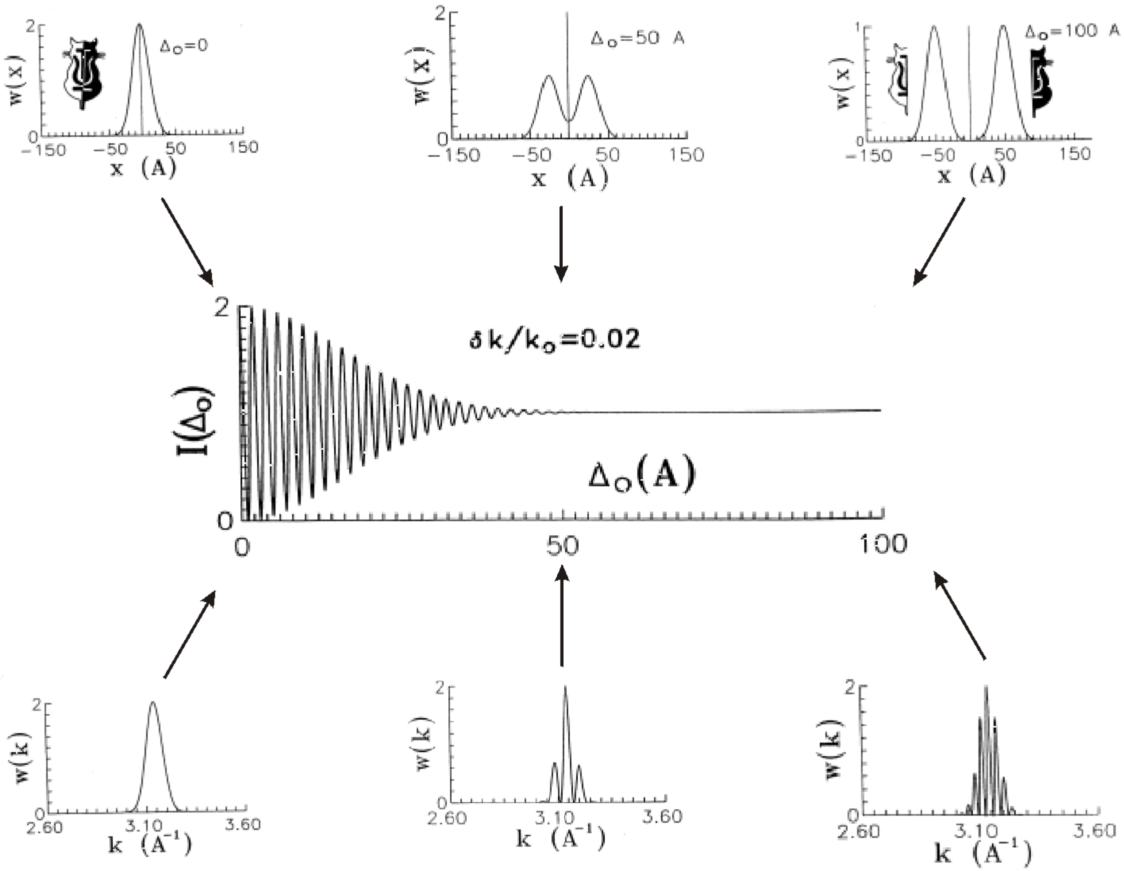
$$\Psi(x) \propto \int a(k) e^{ikx} dx$$





SPATIAL VERSUS MOMENTUM MODULATION

Spatial distribution



$$I_0(x) = \left|\psi(x)+\psi(x+\Delta)\right|^2$$

$$= e^{-\frac{x^2}{2\delta x^2}} + e^{-\frac{(x+\Delta)^2}{2\delta xx^2}}$$

$$+ 2e^{-\frac{x^2}{4\delta xx}}\, e^{-\frac{(x+\Delta)^2}{44\delta x^2}} \cos\chi_0$$

$$I_0(k) = \exp^{-\frac{(k-k_0)^2}{2\delta k^2}}\left[1+\cos(\chi_0 \frac{k_0}{k})\right]$$

Momentum distribution

WIGNER FUNCTION

Definition:

$$W(k,x) = \frac{1}{4\pi}\int e^{ik\Delta}\psi^*\left(x+\frac{\Delta}{2}\right)\psi\left(x-\frac{\Delta}{2}\right)d\Delta$$

Properties:

$$\int W(k,x)dk = |\psi(x)|^2$$

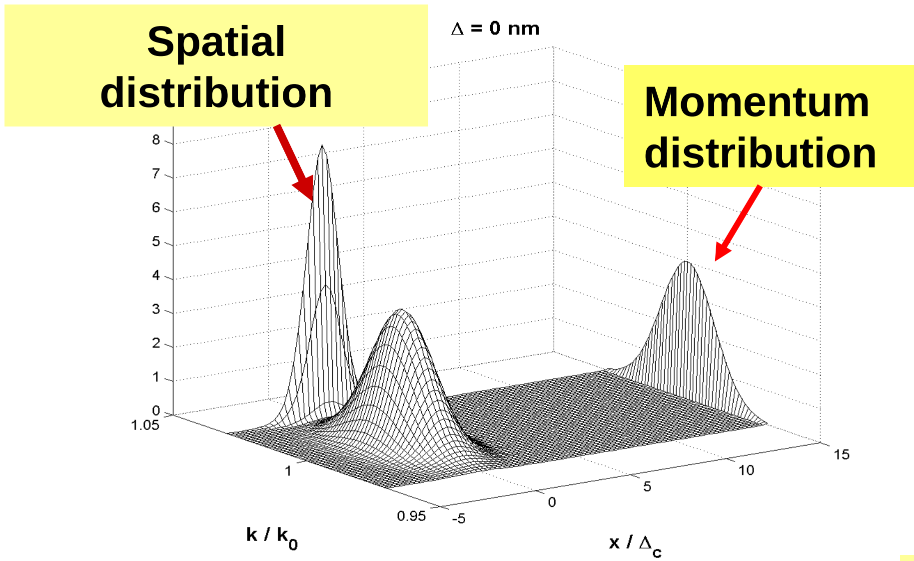
$$\int W(k,x)dx = |\psi(k)|^2$$

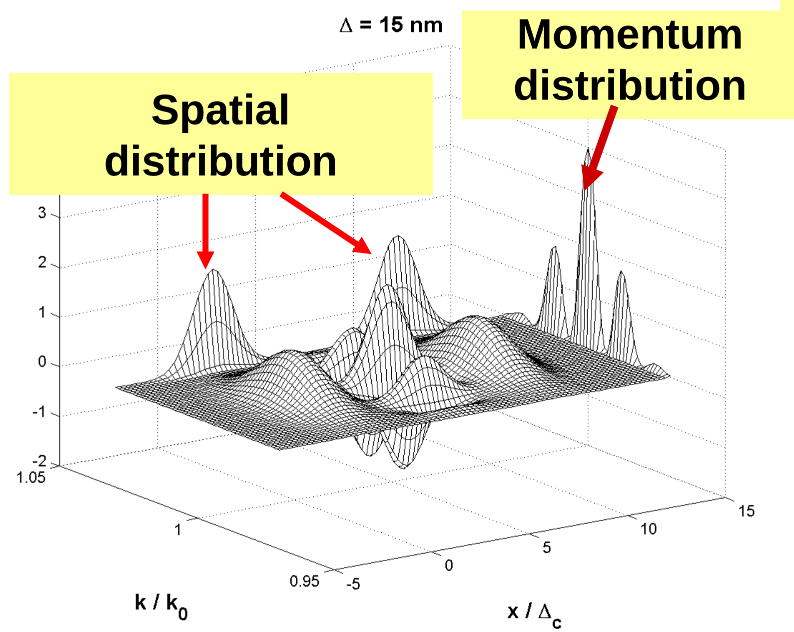
Interferometric Gaussian packets:

$$\psi^{I,II}(x) = \left(4\pi\delta x^2\right)^{-1/4}\exp\left[-x^2/2\delta x^2 + ixk_0\right]$$

$$\psi(x) = \psi^{I}(x) + \psi^{II}(x+\Delta_0)$$

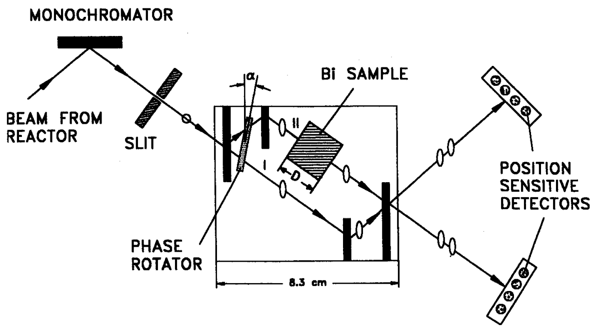
H. Rauch, M. Suda, Appl.Phys.B60 (1994) 181



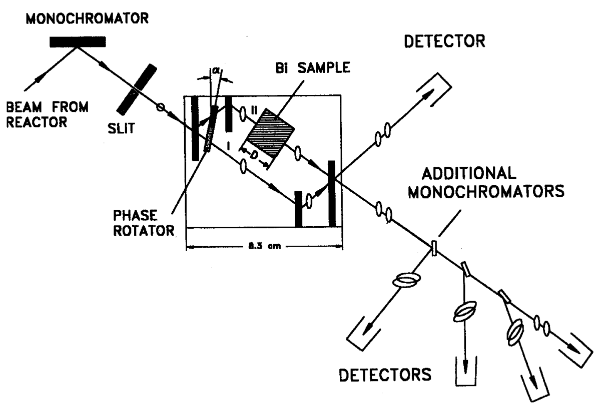


Post-selection methods

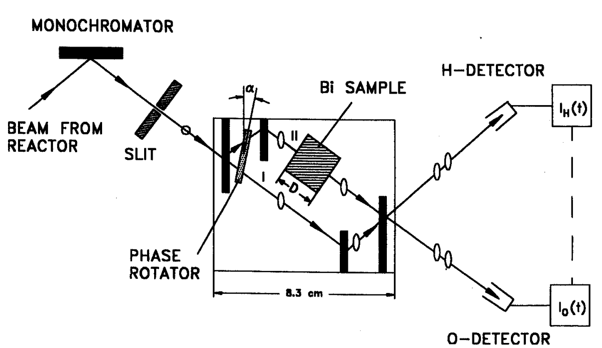
POSITION POSTSELECTION



MOMENTUM POSTSELECTION



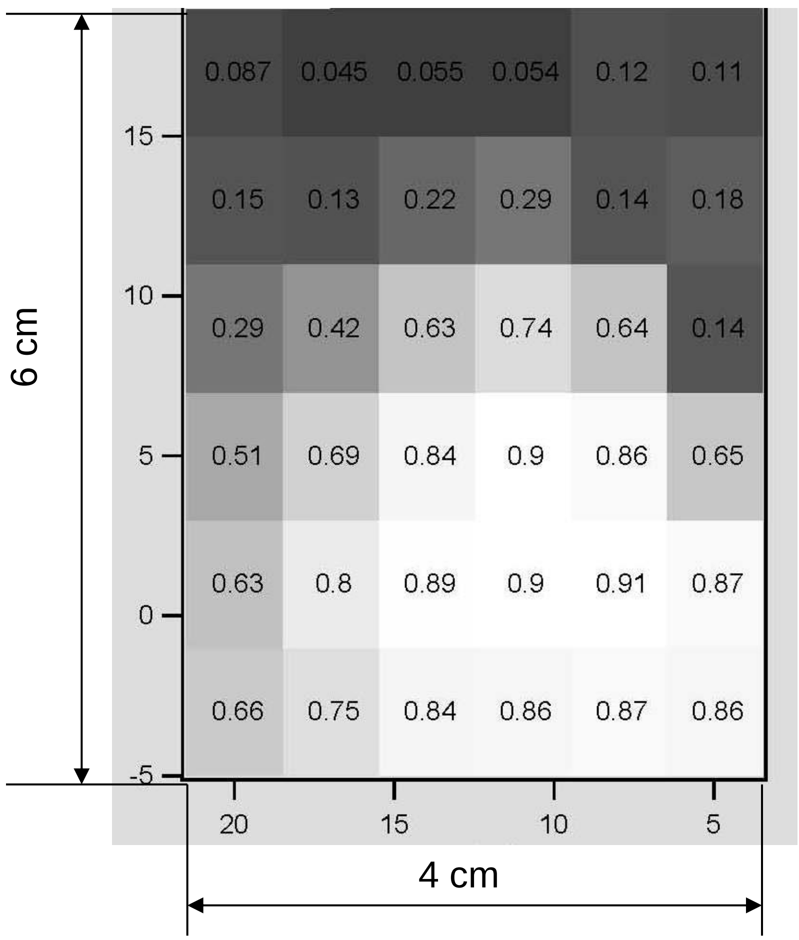
TIME POSTSELECTION



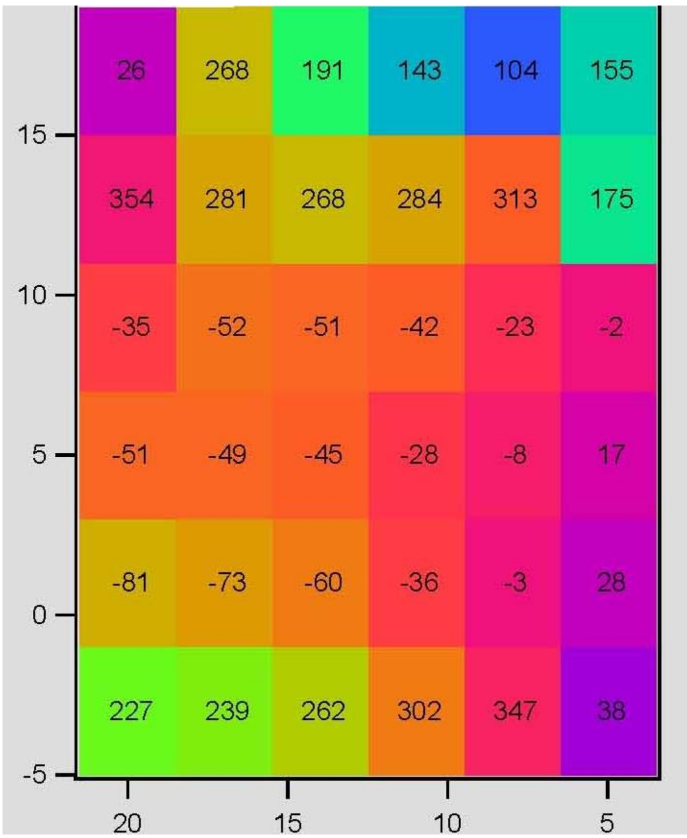
More information – less mystics - due to post-selection !

Position Post-Selection

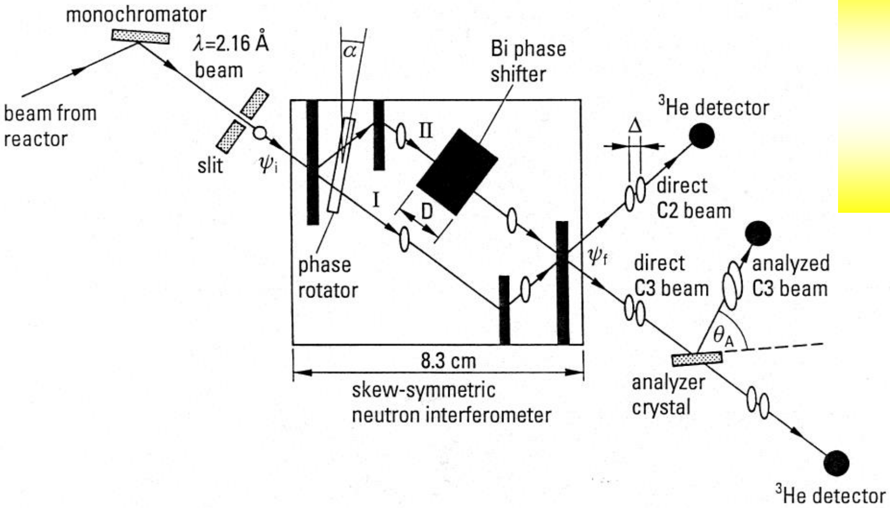
contrast



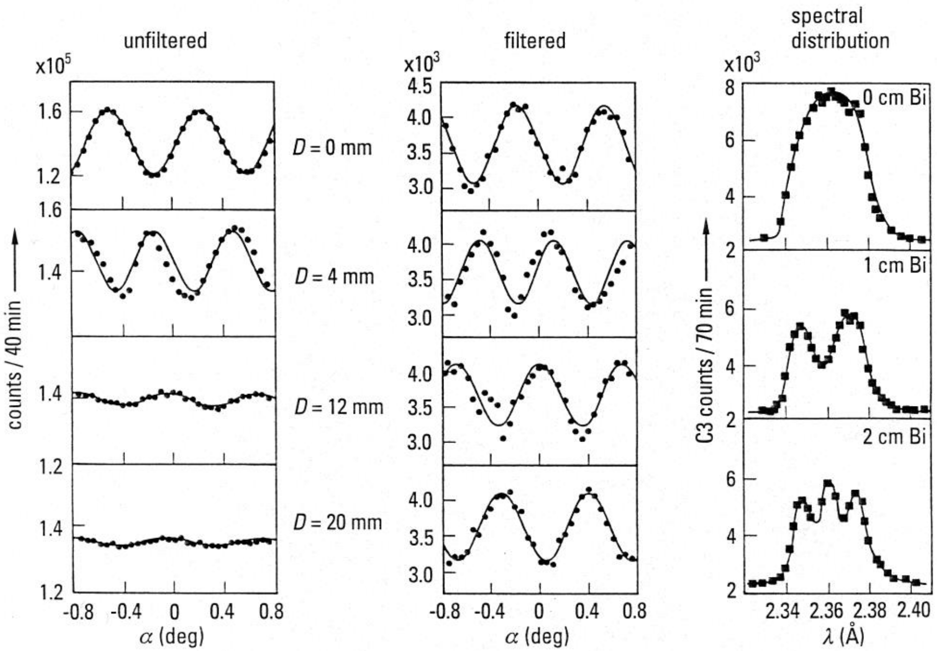
internal phase



Momentum Post-selection



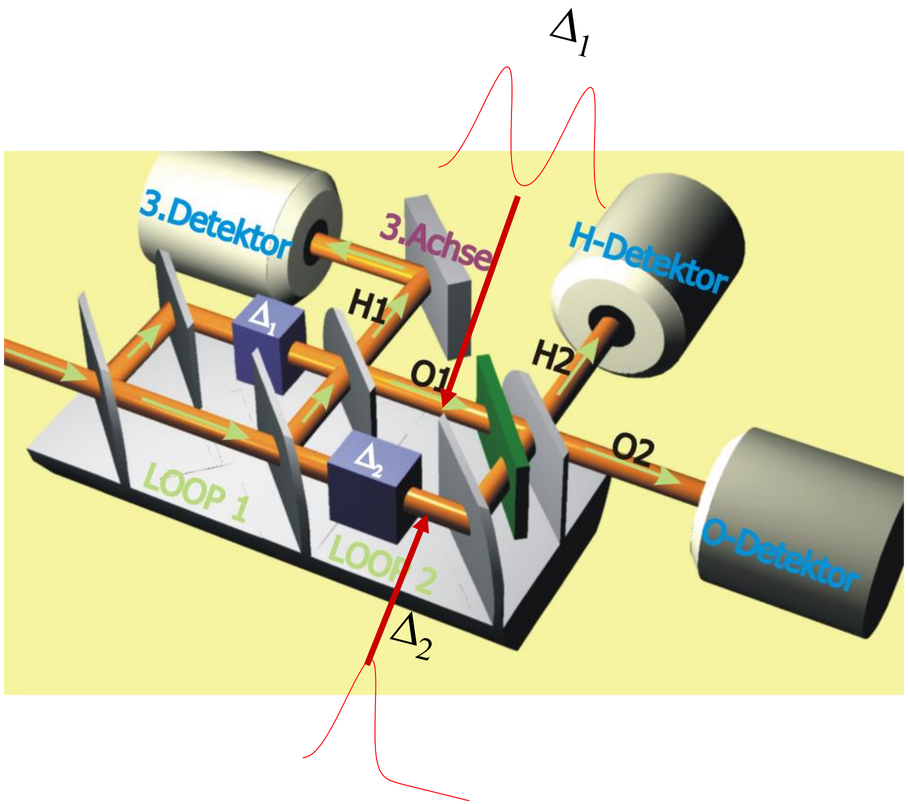
Verification of Schrödinger cat-like states

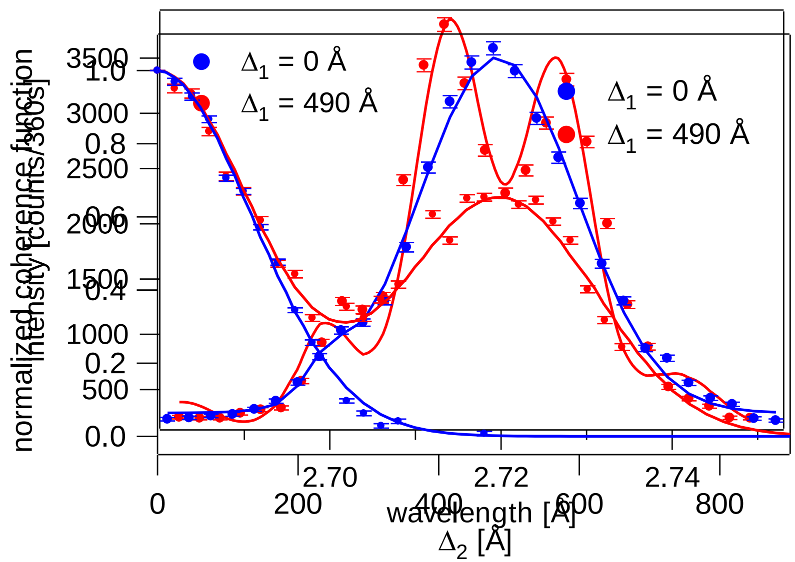


$$I_0(k) \propto g(k)\left[1-\cos\left(\chi_0 \frac{k}{k\partial}\right)\right]$$

D.L. Jacobson, S.A. Werner, H. Rauch, Phys.Rev A49 (1994) 3196

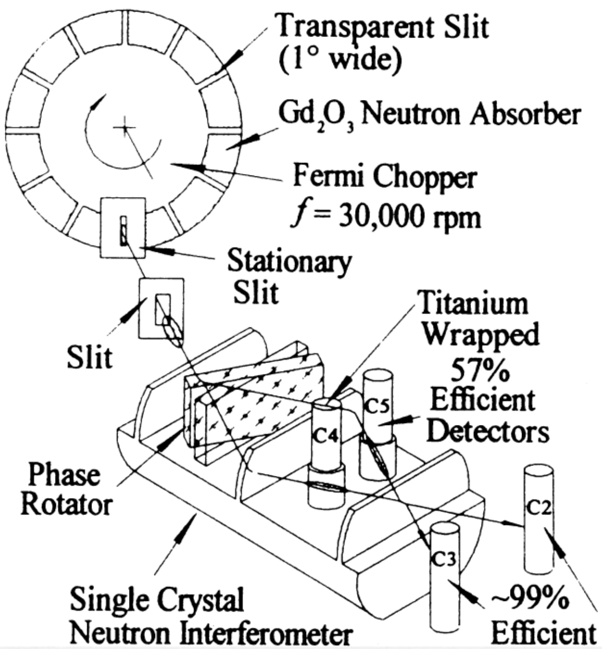
Wave Packet Structure



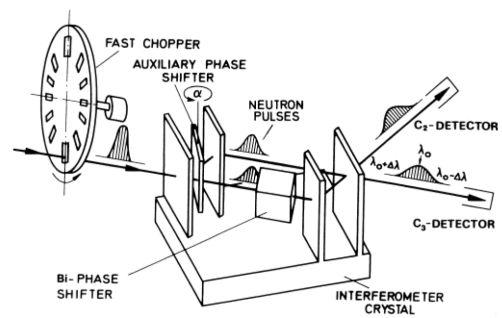


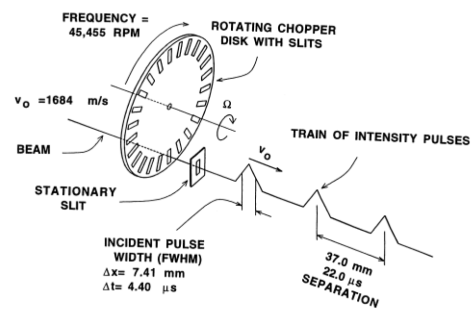
M.Baron, H.Rauch, M.Suda, J.Opt.B5 (2003) S341

Time-Postselection

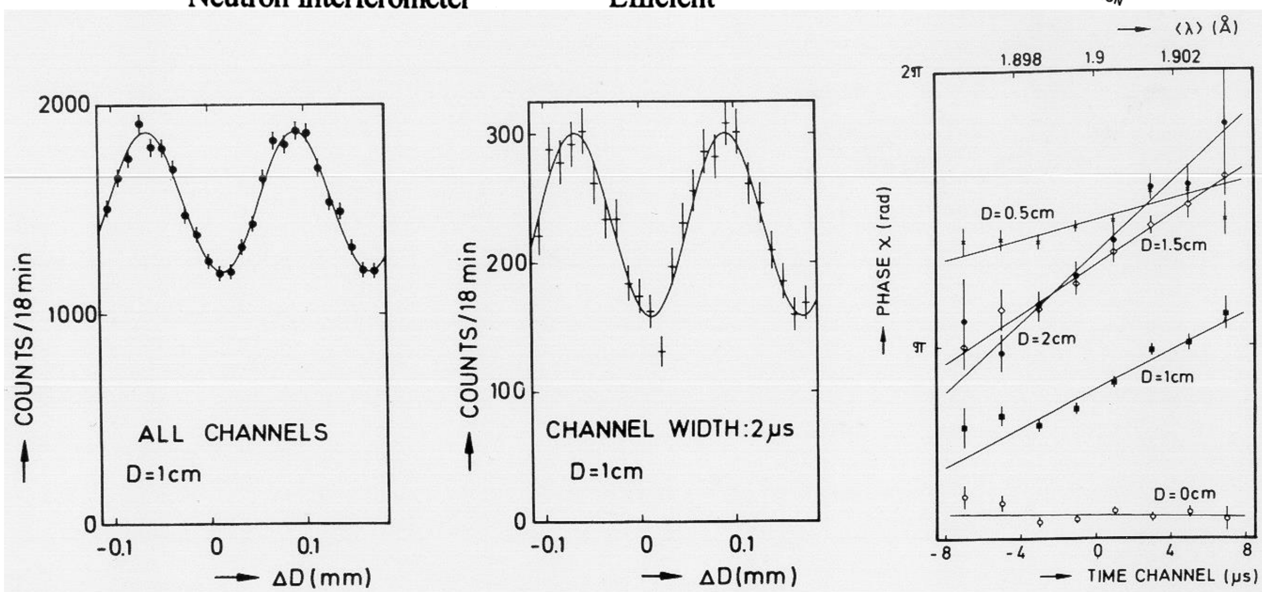


D.L. Jacobson, B.E. Allman, M. Zawisky, S.A. Werner, H. Rauch (1996) J.Jap.Phys.Soc. A65, 94

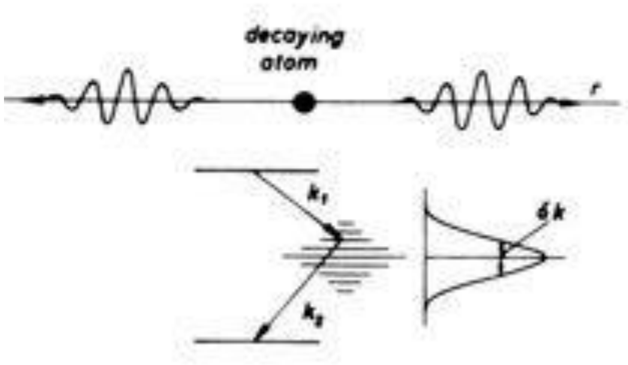


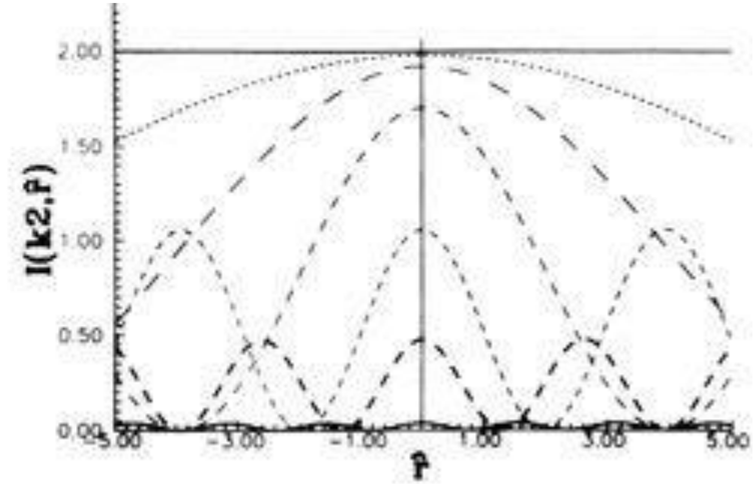


H. Rauch, H. Wölwitsch, R. Clothier, S.A. Werner (1992) Phys. Rev. A46, 49



EPR-Photon Experiment





$|k_1-k_2|=n\delta k$

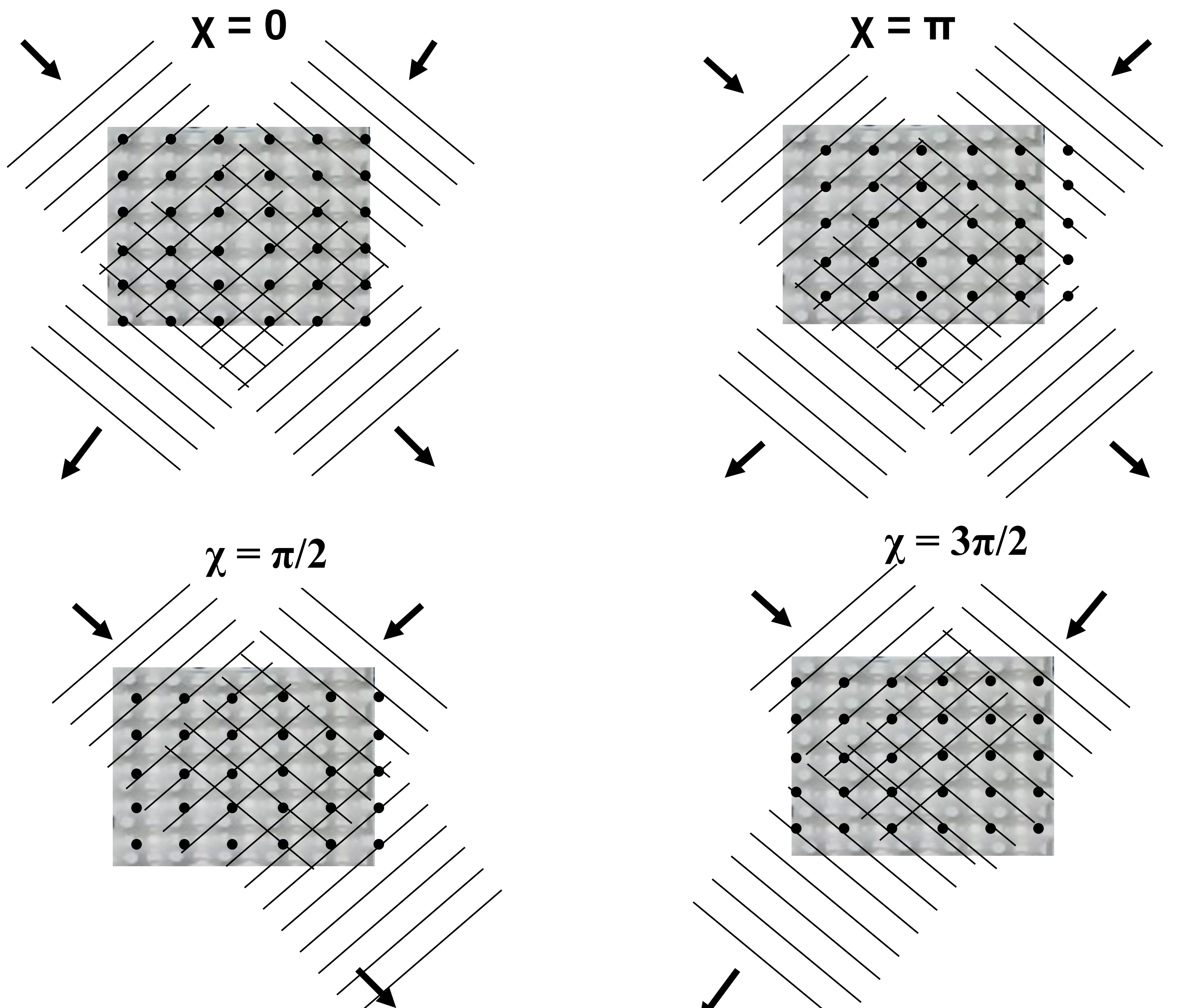
———	0
··········	0.1
-·-·-·-·	0.5
- - - - -	1
— — — —	2

$$\psi_{\alpha,\beta}^{singlet} \propto \left[|+>_\alpha |->_\beta - |->_\alpha |+>_\beta \right] \psi_\alpha \psi_\beta$$

$$k_\alpha + k_\beta \quad = \quad k_{0\alpha} + k_{0\beta} \quad = \quad const$$

$$I(k_\alpha, k_\beta, r) \quad \propto \quad 1 + \cos\left[2(k_\alpha - k_\beta) r\right]$$

Wave – Lattice Interaction



Quantum potential

$$\psi(\vec{r},t) \quad = \quad R(\vec{r},t)\, e^{iS(\vec{r},t)/\hbar}$$

$$\frac{\partial R^2}{\partial t} + \vec{\nabla}\left(R^2 \frac{\vec{\nabla} S}{m} \right) \quad = \quad 0$$

$$\frac{\partial S}{\partial t} + \frac{1}{2m}(\vec{\nabla} S)^2 + V - \frac{\hbar^2}{2m}\frac{\vec{\nabla}^2 R}{R} \quad = \quad 0$$

$$Q \quad = \quad -\frac{\hbar^2}{2m}\frac{\vec{\nabla}^2 R}{R}$$

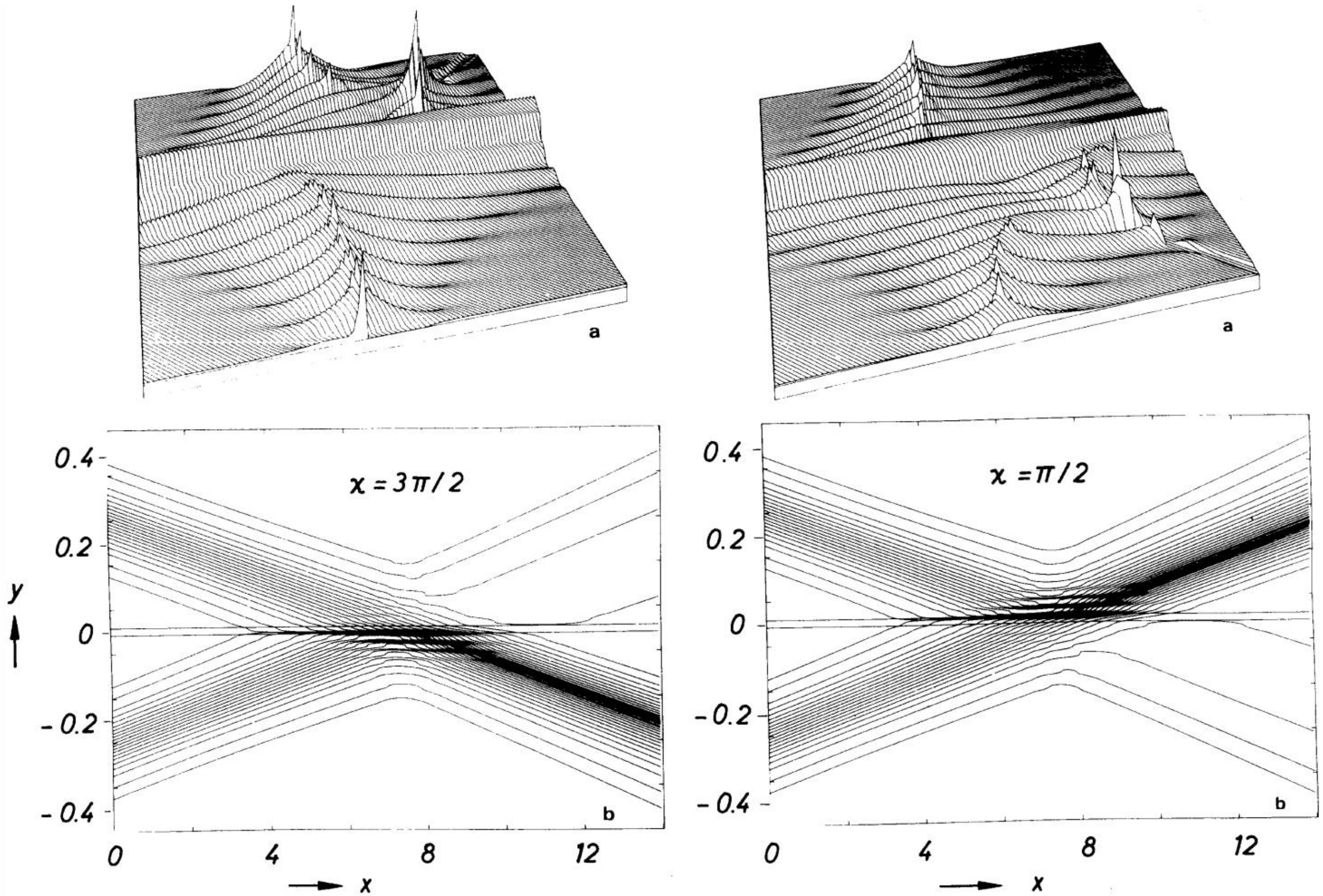
$$\rho(\vec{r},t) = R^2(\vec{r},t) = \left|\psi(\vec{r},t)\right|^2$$

$$m\vec{v}(\vec{r},t) \quad = \quad \vec{\nabla} S(\vec{r},t)$$

Bohm D. (1952a) *Phys. Rev.* 85, 166

Bohm D. (1952b) *Phys. Rev.* 89, 180

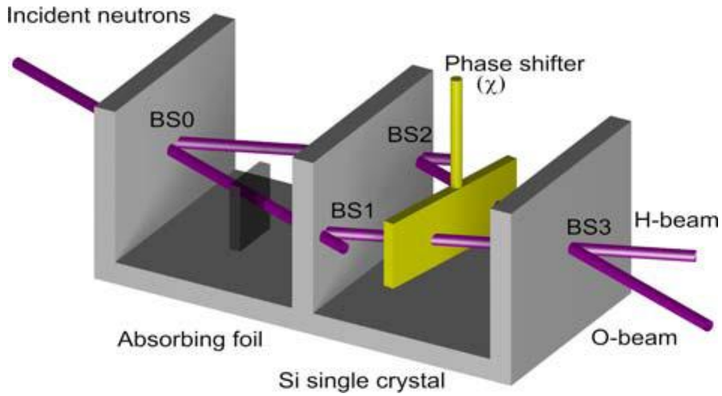
Quantum potential and trajectories



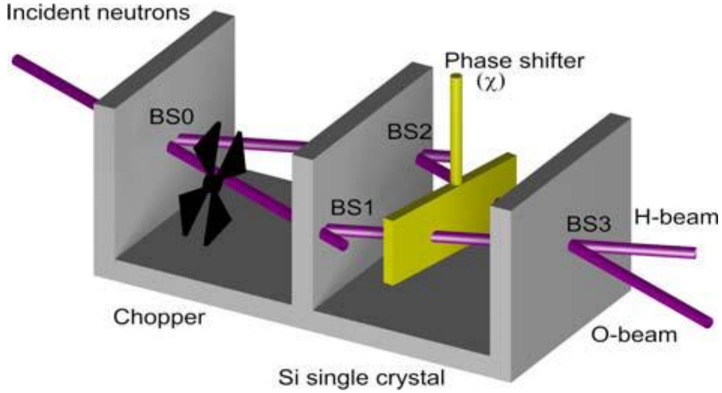
C. Dewdney, P.R. Holland, A. Kyprianidis (1986) Phys. Rev. A119, 259

Weak Measurements

Absorbing phase shifter



stochastic



deterministic

$$\psi' = \psi\, e^{i(\chi' + i\chi'')} = \psi \sqrt{a}\, e^{i\chi'}$$

$$a = \frac{t_{open}}{t_{open} + t_{closed}}$$

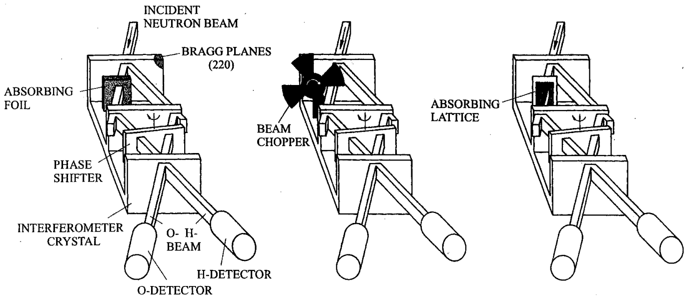
$$\chi'' = (\sigma_a + \sigma_{inc}) ND / 2 \qquad a = \frac{I}{I_0} = e^{(\sigma_a + \sigma_{inc}) ND}$$

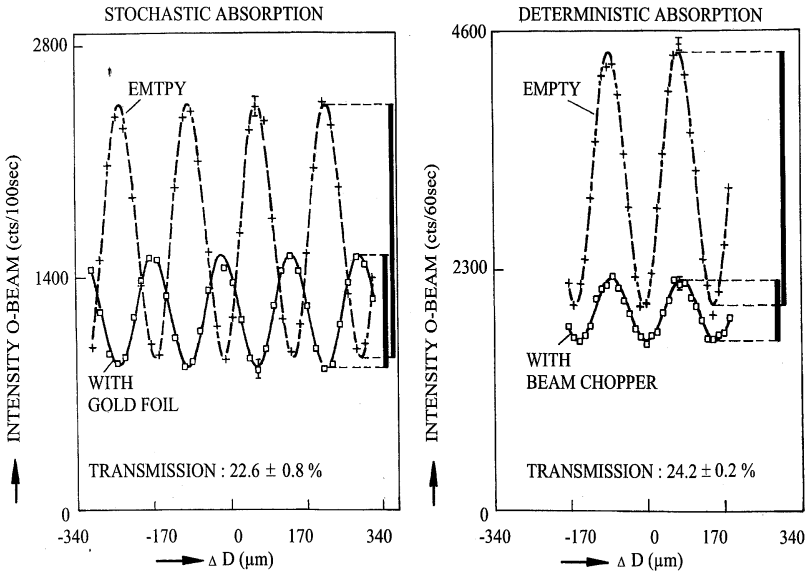
$$I_{det} \propto \left[(1-a) \left| \Psi_0^{II} \right|^2 + a \left| \Psi_0^{I} + \Psi_0^{II} \right|^2 \right]$$

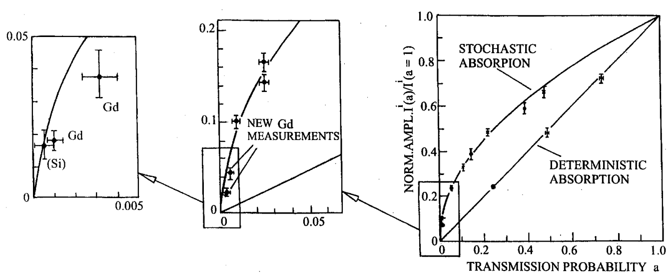
$$\propto \left| \Psi_0^{I} \right|^2 \left[(1+a) + 2a \cos \chi' \right]$$

$$I_{sto} = \left| \psi_0{}^{I} + \psi_0{}^{II} \right|^2 \propto \left| \psi_0{}^{I} \right|^2 \left((a+1) + 2\sqrt{a} \cos \chi' \right).$$

Absorption results







J. Summhammer, H. Rauch, D. Tuppinger, Phys.Rev. A 36 (1987) 4447

Small a-case:

$$\chi'' = (\sigma_a + \sigma_{inc}) ND / 2$$

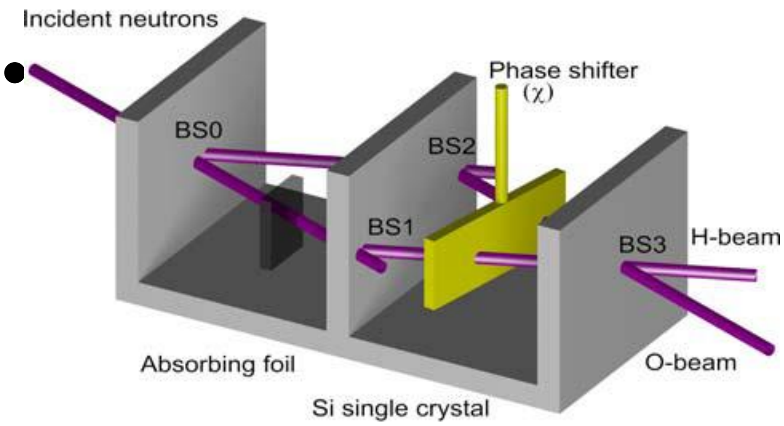
$$\chi'' \rightarrow \chi''_0 + \delta\chi''$$

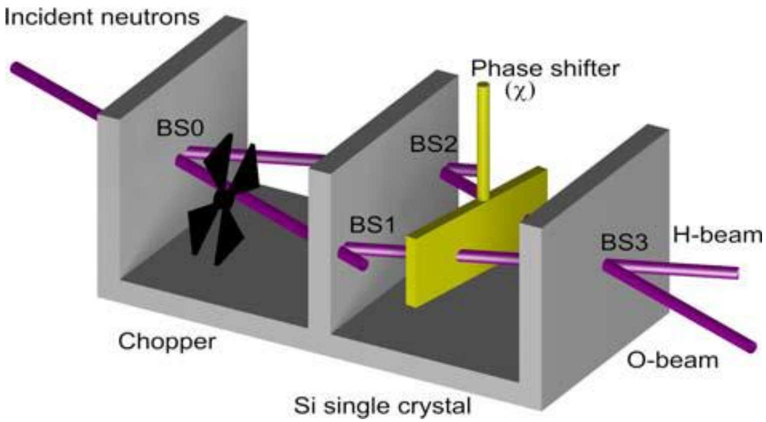
$$\overline{e^{(\sigma_a + \sigma_{inc})ND}} = \overline{\sqrt{a}} = \overline{e^{-(\chi + \delta\chi'')}} = \sqrt{a_0} e^{(\delta\chi'')^2 / 2}$$

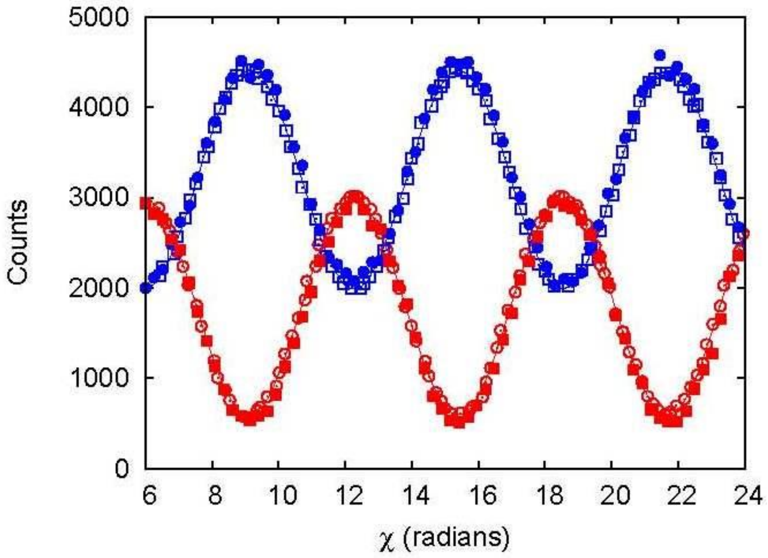
$$\bar{a} = a_0 e^{2(\delta\chi'')^2}$$

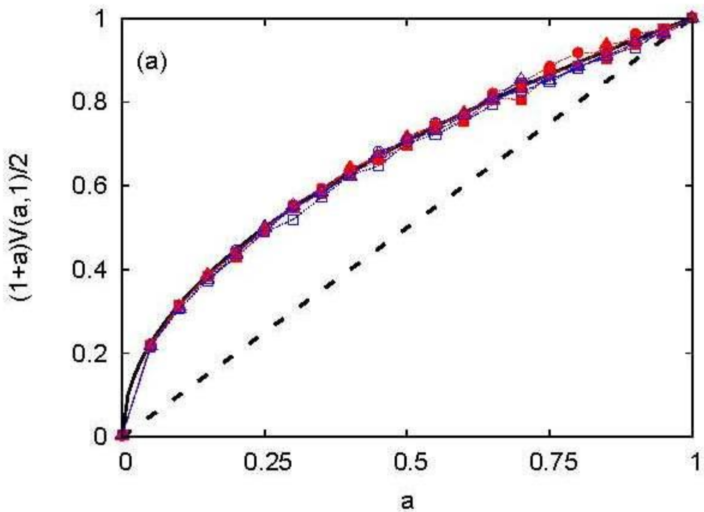
$$\sqrt{a} < \sqrt{a_0}$$

Event by event simulation



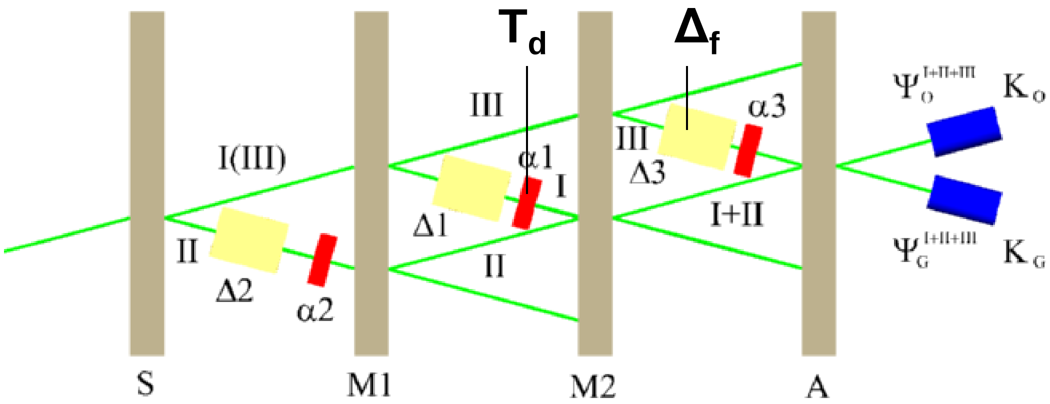






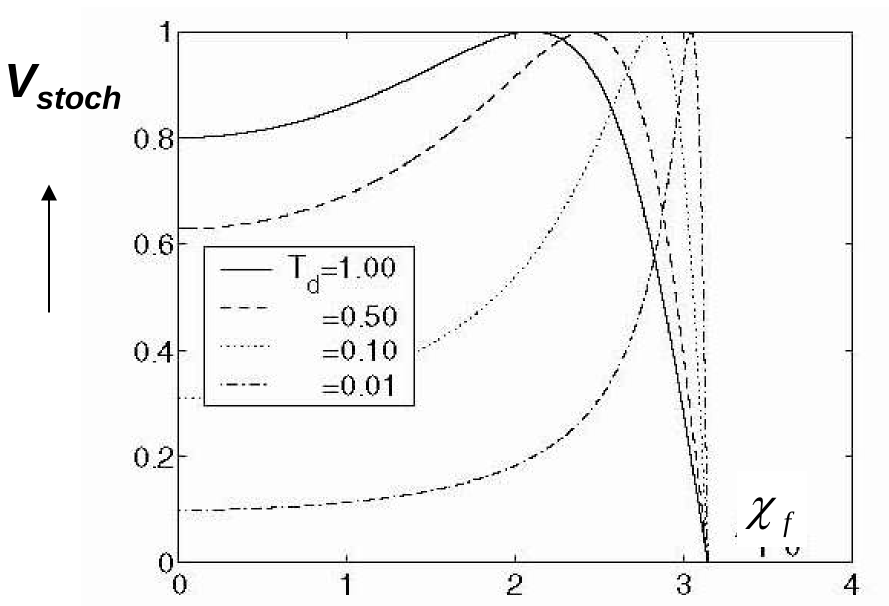
H. De Raedt, F. Jin, K. Michielsen, Quantum Matter 1 (2012) 20

Double Loop Visibility



$$V = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

$$V_{sto2\Delta_f} = \frac{4\sqrt{T_d}\cos(\chi_f/2)}{4\cos^2(\chi_f/2) + T_d}$$

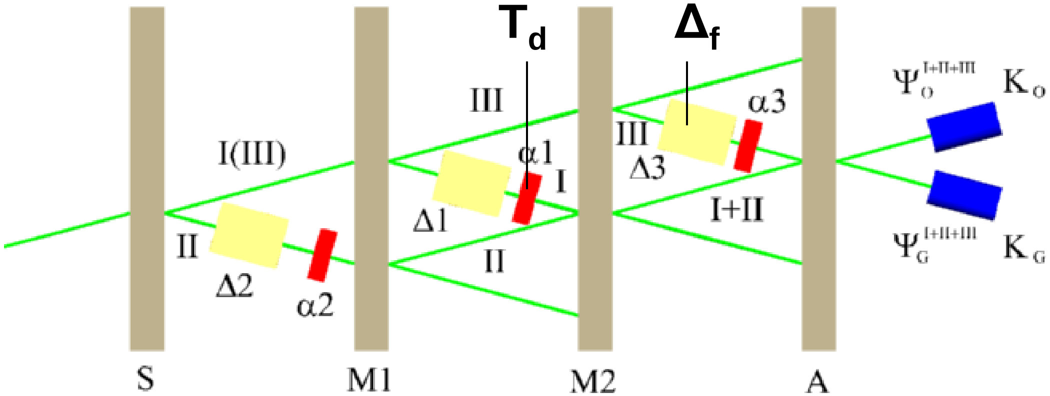


$$V_{sto2\Delta_f} = 1 \quad if \quad T_d = 4\cos^2(\Delta_f k_0/2)$$

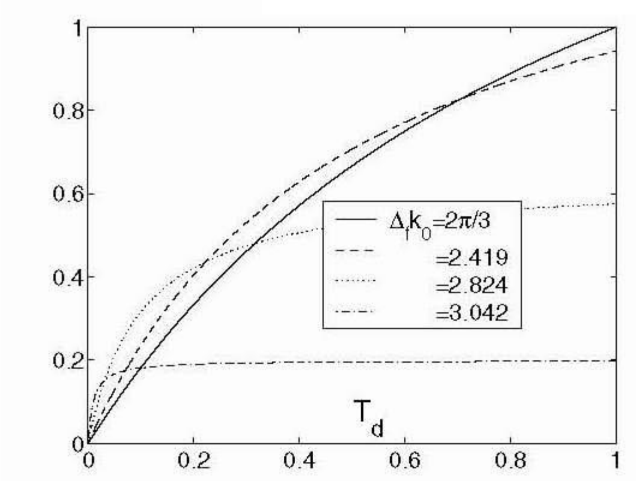
$$\Rightarrow \text{homodyne detection}$$

M. Suda, H. Rauch, M. Peev,
J.Opt.B:Quantum Semiclass.Opt. 6(2004)345

Stimulated Coherence

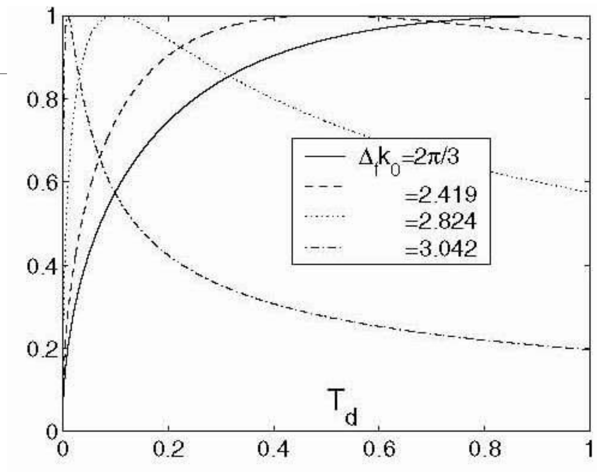


deterministic



$$V_{\det 2\Delta_f} = \frac{4T_d \cos(\Delta_f k_0/2)}{4\cos^2(\Delta_f k_0/2) + T_d} \leq 1$$

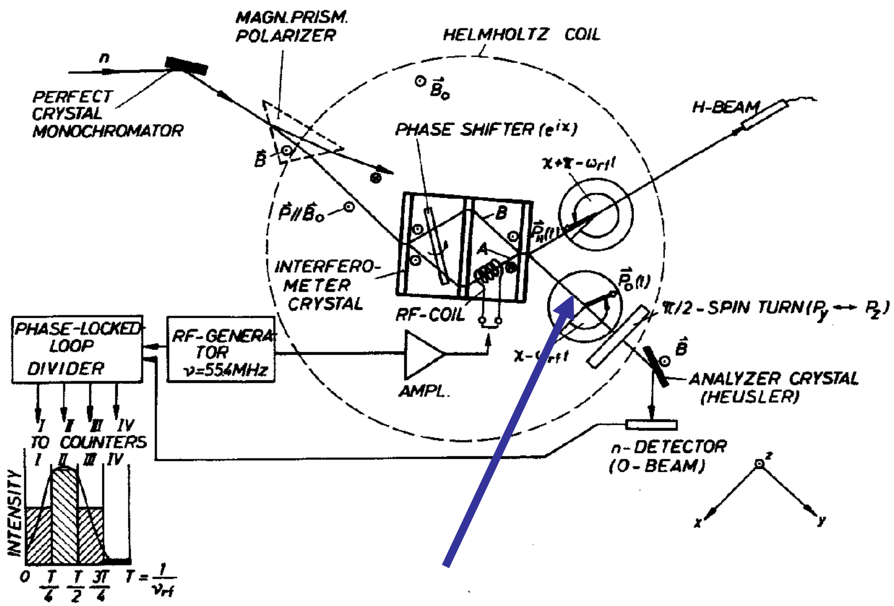
stochastic

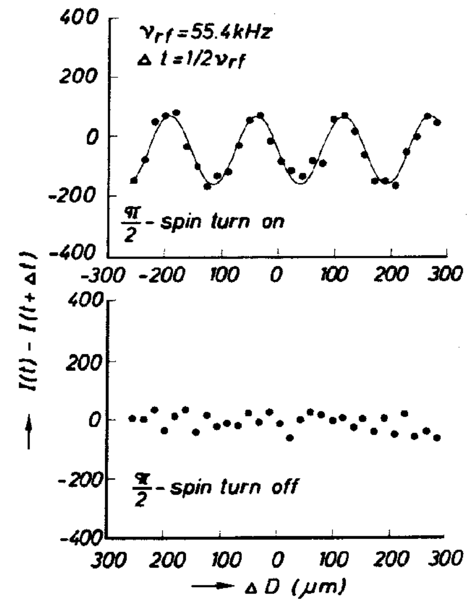


$$V_{sto2\Delta_f} = \frac{4\sqrt{T_d}\cos(\chi_f/2)}{4\cos^2(\chi_f/2) + T_d}$$

Active neutron-apparatus interaction

Dynamic Spin-Superposition (One photon exchange)





G. Badurek, H. Rauch, J.Summhammer, Phys. Rev.Lett. 51 (1983) 1015

Zero-field Larmor precession

$$\Psi(\chi,\omega_r) = e^{-i\chi} e^{-i(\omega-\omega_r)t} \left| -z \right\rangle$$

$$\vec{P} = \begin{pmatrix} \cos(\chi-\omega_r)t \\ \sin(\chi-\omega_r)t \\ 0 \end{pmatrix}$$

one photon exchange:

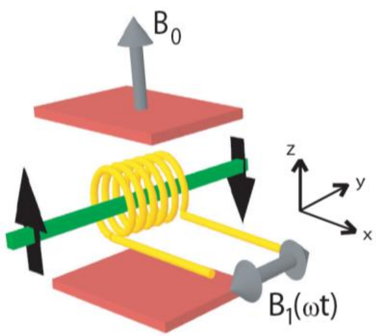
Photon exchange but no path information:

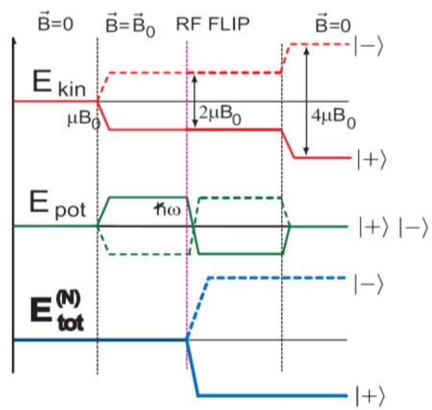
$\Delta N \Delta \phi > 1/2$

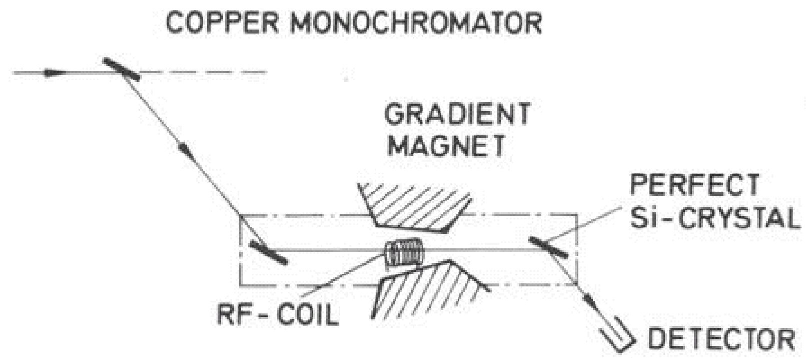
$\Delta v_r = 2mB/mv < \Delta v_{beam}$

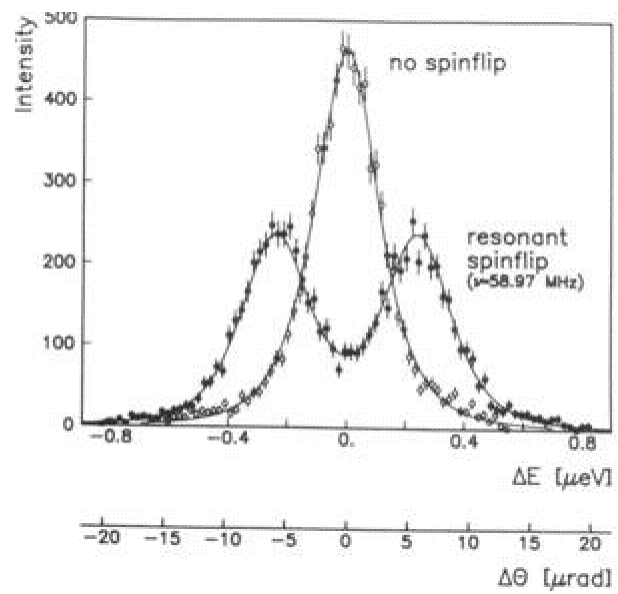
$\Delta t < \Delta l / \Delta v_r < 2\pi/\omega_r$; $\Delta l \Delta k < 1/2$

On-resonance→ single photon exchange









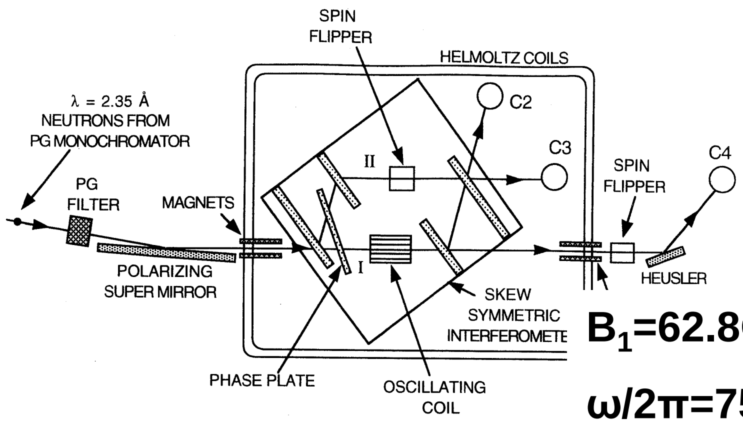
$$\hbar\omega_r = 2\mu B_0$$

$$B_1 = \frac{\pi\hbar v_n}{2\mu l}$$

H.Weinfurter, G.Badurek, H.Rauch, D.Schwahn, Z.Phys. B72(1988)195

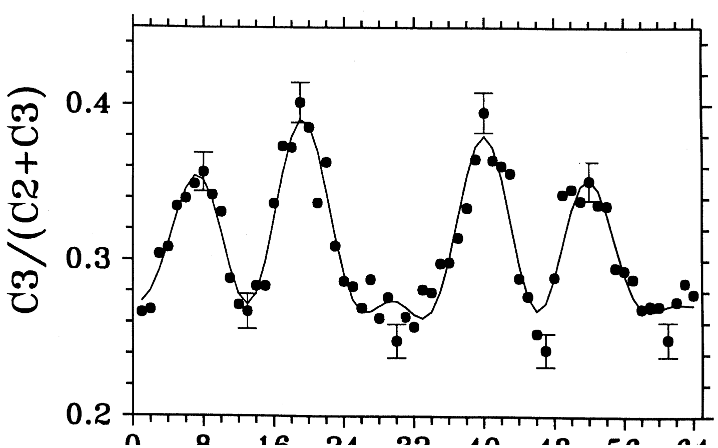
Noise field and dephasing

(Multi photon exchange)



B_1=62.8G

ω/2π=7534 Hz



$$\vec{B}(t) = \begin{pmatrix} 0 \\ 0 \\ B_0 + B_1 \cos \omega\, t \end{pmatrix}$$

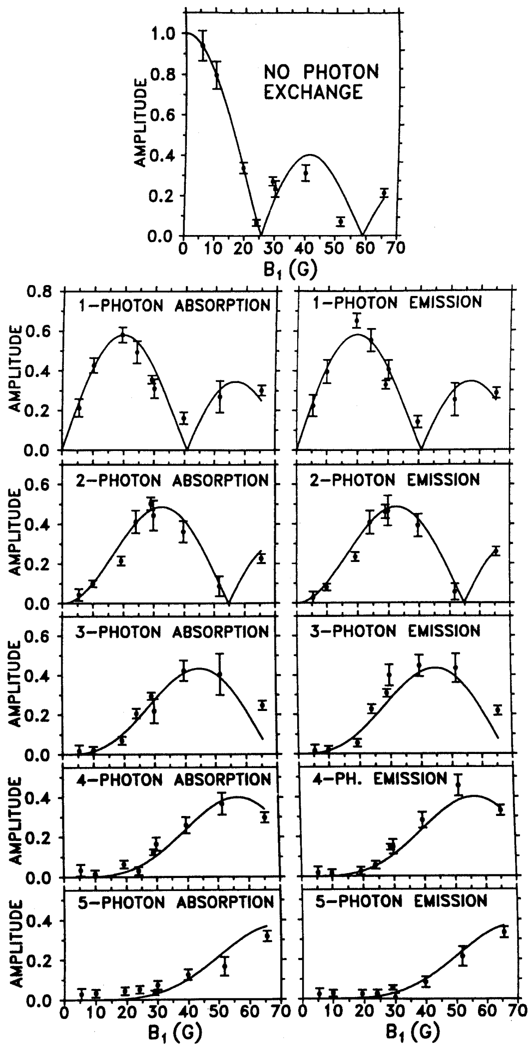
$$\left|\psi_f\right\rangle = \sum_{j=-\infty}^{j=+\infty} \left[a_j \left|+z\right\rangle + b_j \left|-z\right\rangle \right] e^{i\omega_j t}$$

$$\omega_j = \omega_0 + j\,\omega$$

$$a_j = J_j(\alpha\, B_1) \qquad \alpha = \frac{\mu}{\hbar\omega} \sin(\omega\tau / 2)$$

$$I \propto \left| \left|+z\right\rangle + e^{i\chi} \left|\psi_f\right\rangle \right|^2 = 1 + \left| \sum_{j=-\infty}^{+\infty} \left(a_j \left|+z\right\rangle + b_j \left|-z\right\rangle\right) e^{-ij\omega t} \right|^2 + 2 \sum_{j=-\infty}^{j=\infty} \left|a_j\right| \cos(\phi_j + \chi - j\omega t)$$

Multi-photon exchange: results

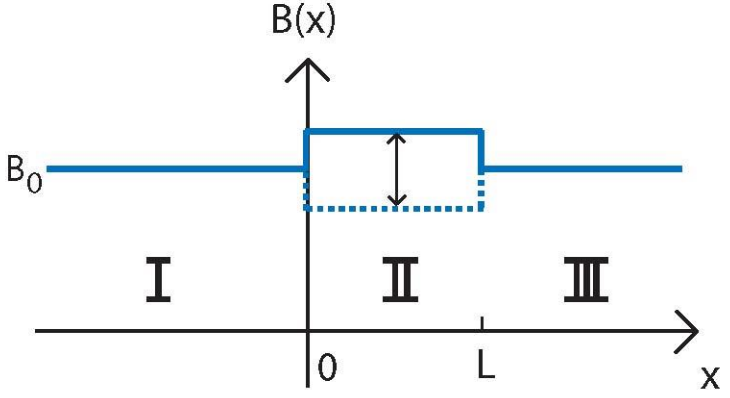


ν = 7534 Hz → ΔE= 3.24.10^{-11}eV

<< ΔE_{beam} = 10^{-4}eV

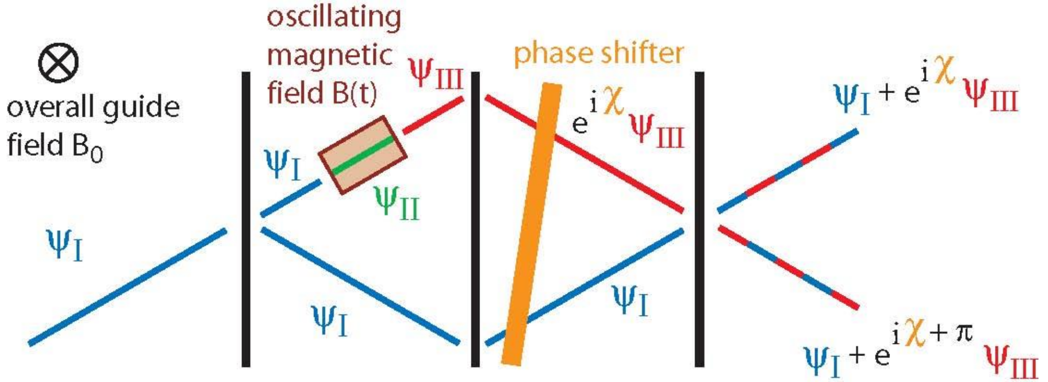
J. Summhammer, K.A. Hamacher, H. Kaiser, H. Weinfurter, D.L. Jacobson, S.A. Werner, Phys.Rev.Lett. 75 (1995) 3206

Mono- and multi-mode noise



$$i\hbar \frac{\partial \psi(\vec{r},t)}{\partial t} = H\psi(\vec{r},t) = \left(\frac{\hbar^2 k^2}{2m} + \mu\hat{\sigma}B(\vec{r},t) \right)\psi(\vec{r},t)$$

$$\vec{B}(\vec{r},t) = \left[B_0 + B(t).(\Theta(x) - \Theta(x-L)) \right]\hat{z}$$



$$B(t) = \sum_{i=1}^{N} B_i \cos(\omega_i t + \varphi_i)$$

Formalism

$$i\hbar\frac{\partial\psi(\vec{r},t)}{\partial t}=H\psi(\vec{r},t)=\left(\frac{\hbar^2k^2}{2m}+\mu\hat{\sigma}B(\vec{r},t)\right)\psi(\vec{r},t)$$

$$\vec{B}(\vec{r},t)=\left[B_0+B(t).(\Theta(x)-\Theta(x-L))\right]\hat{z}$$

$$B(t)=\sum_{i=1}^{N}B_i\cos(\omega_i t+\varphi_i)$$

$$\Psi_{III}(x,t)=\sum_{\vec{n}}J_{n_1}(\beta_1)........J_{n_N}(\beta_N)e^{-\vec{n}\vec{\eta}}e^{ik_n x}e^{-i\omega_n t}$$

$$\omega_{\vec{n}}=\omega_0+\vec{n}\vec{\omega}\qquad \vec{k}_{\vec{n}}^2=k_0^2-\frac{2m}{\hbar^2}\mu B_0+\frac{2m}{\hbar}\vec{n}\vec{\omega}$$

$$\eta_i=\varphi_i+\frac{\omega_i T+\pi}{2}\qquad \beta_i=2\alpha_i\sin\frac{\omega_i T}{2}\qquad \alpha_i=\frac{\mu B_i}{\hbar\omega_i}\qquad T=\frac{L}{v_0}$$

$$\vec{n}=(n_1.........n_N),\quad \vec{\varphi}=(\varphi_1........\varphi_N),\quad \vec{\omega}=(\omega_1........\omega_N),\quad \vec{\eta}=(\eta_1.........\eta_N),$$

$$I_0(x,t)=\sum_{m=-\infty}^{m=\infty}c_m(x)e^{im\omega_f t}$$

$$c_m=\delta_{m0}+\sum_{\substack{\vec{n};\vec{n}\vec{\omega}=m\omega_f\\ \sum_i n_i even}}J_{n_1}(\beta_1).......J_{n_N}(\beta_N)e^{i\vec{n}\vec{\xi}}\cos\chi$$

$$\langle I_0\rangle=\frac{1}{M}\sum_{i=1}^{M}I_0(t_i)\approx\frac{1}{T_m}\int_0^{T_m}I_0(t_i)dt$$

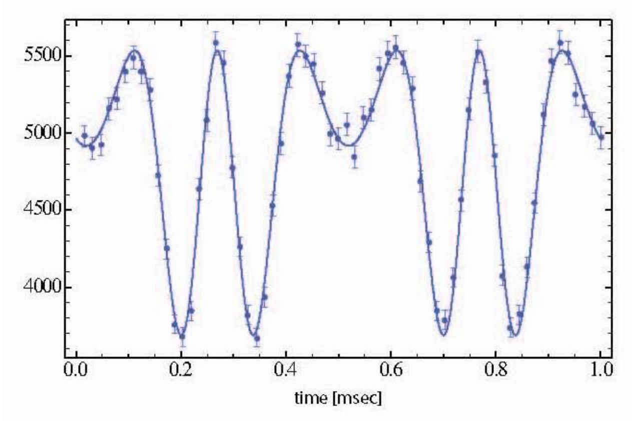
$$C=\frac{1}{T_m}\int_0^{T_m}\cos\left(\sum_{i=1}^{N}\beta_i\left(\omega_i t+\xi_i\right)\right)dt$$

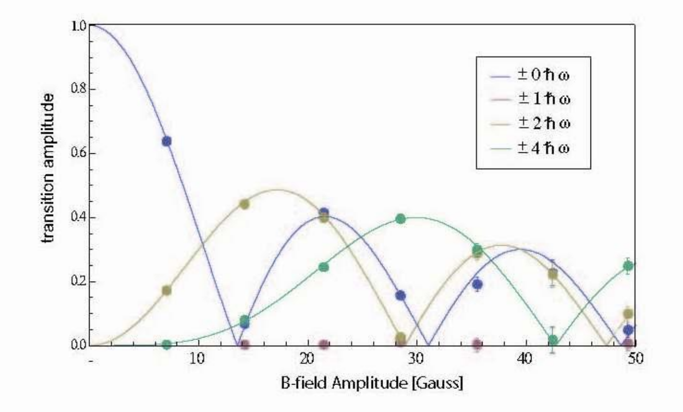
$$I_0(x.t)=\frac{1}{2}\left|\Psi_I(x,t)+e^{i\chi}\Psi_{III}(x.t)\right|^2=1+\mathrm{Re}\left\{e^{i\chi}\sum_{\vec{n}}J_{n_1}.......J_{n_N}.e^{i\vec{n}(\xi_i+\vec{\omega}t)}\right\}$$

$$with\quad \xi_i=\eta_i-\frac{\omega_i x}{v_0}$$

Multi-frequency photon exchange

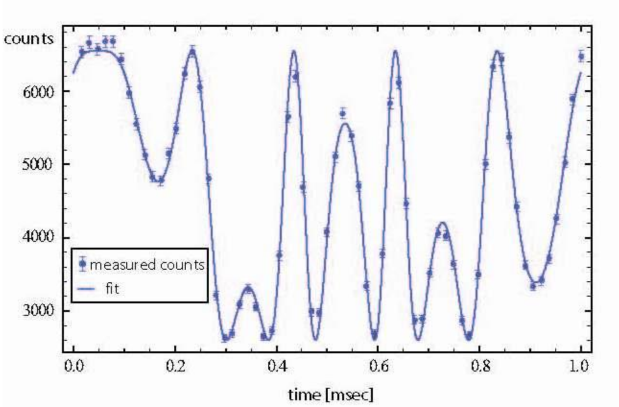
one frequency

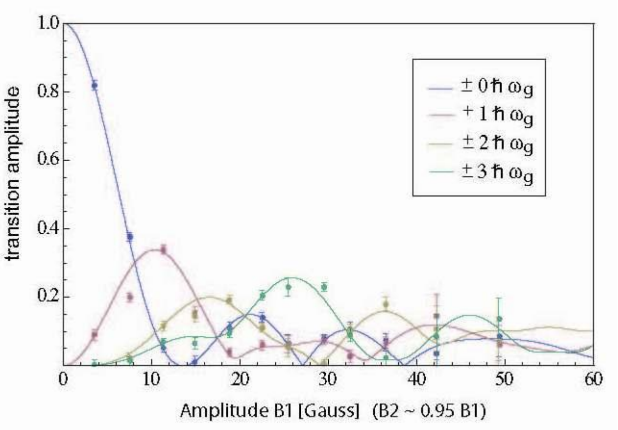




ω_1= 1 kHz, B_1= 40 G

two frequencies



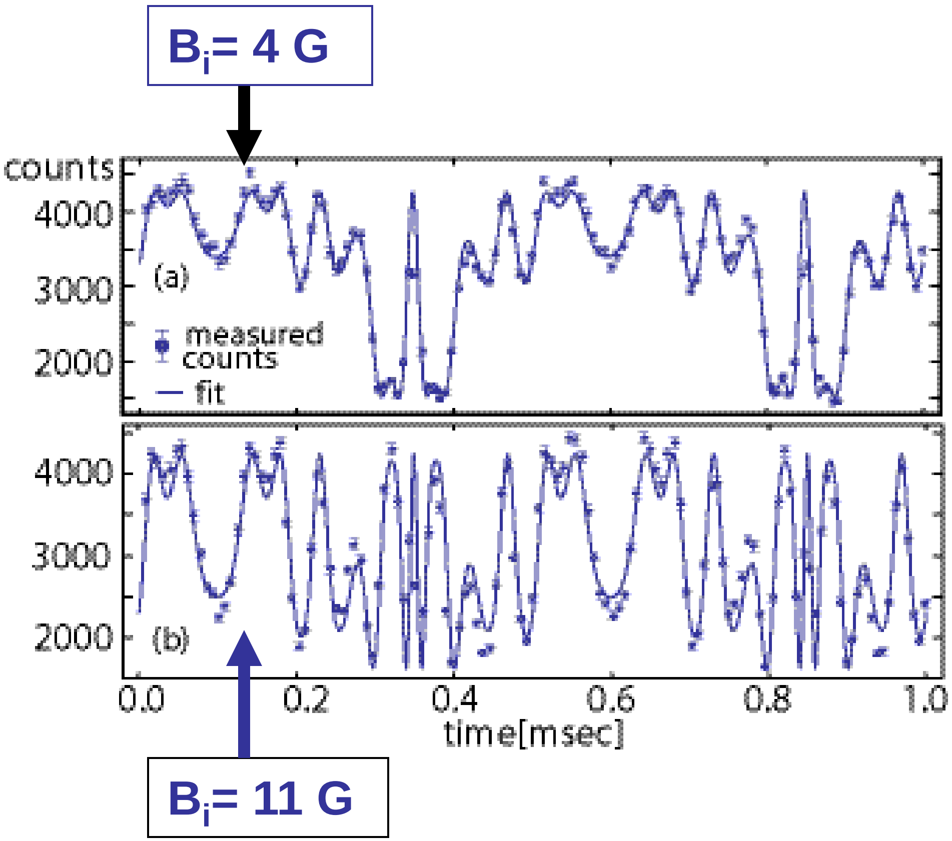


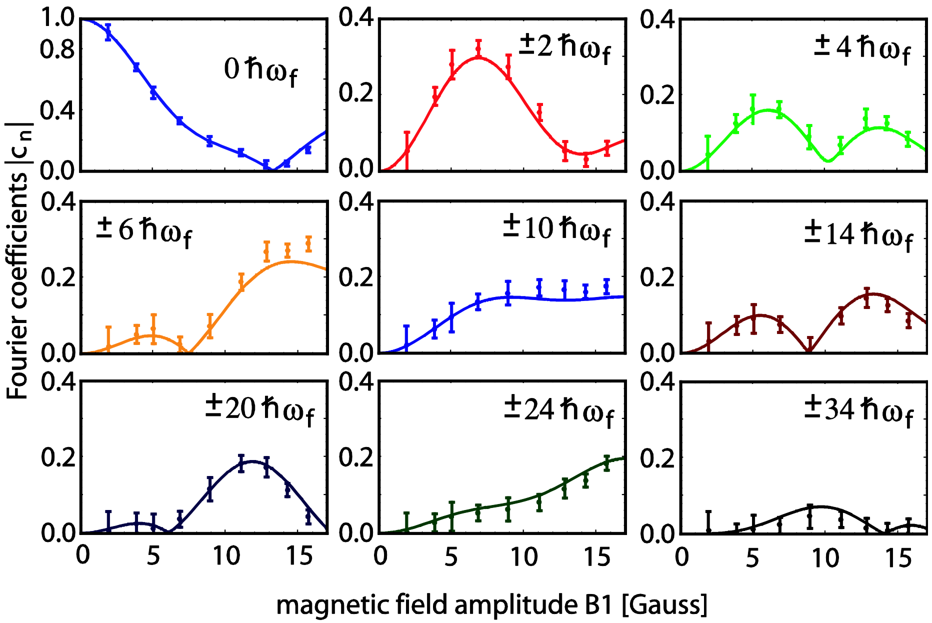
ω_1= 2 kHz; ω_2= 3 kHz;

B_1= 15 G; B_2= 14.2 G

G. Sulyok, H. Lemmel, H. Rauch, Phys.Rev. A85 (2012) 033624

Five-mode case



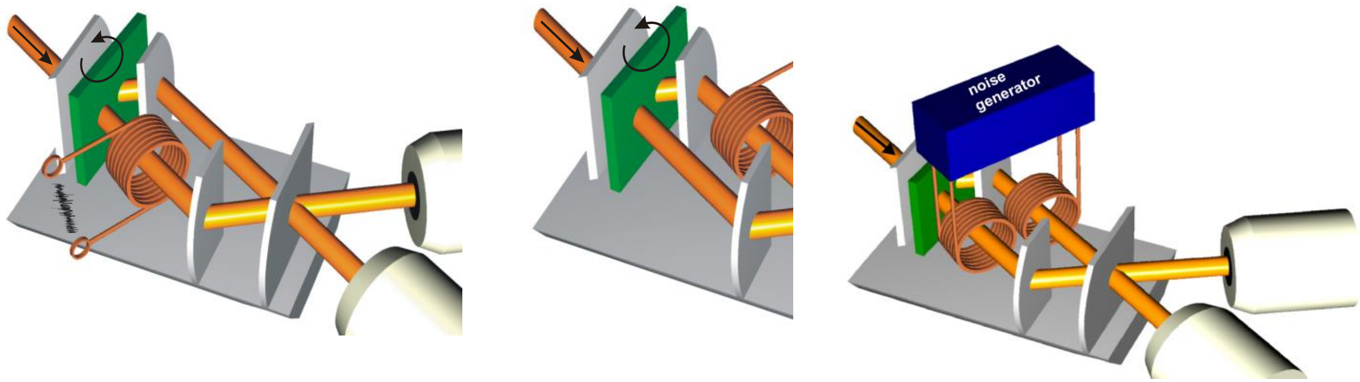


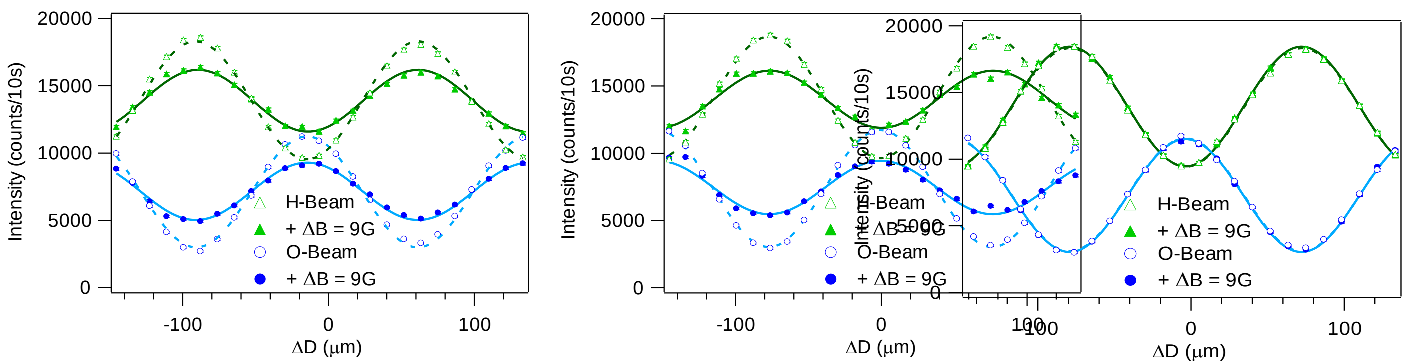
f_1= 3kHz, f_2=5kHz, f_3=7kHz,
f_4=11kHz, f_5=13kHz

G. Sulyok, H. Lemmel, H. Rauch, Phys.Rev. A85 (2012) 033624

Dephasing at low order

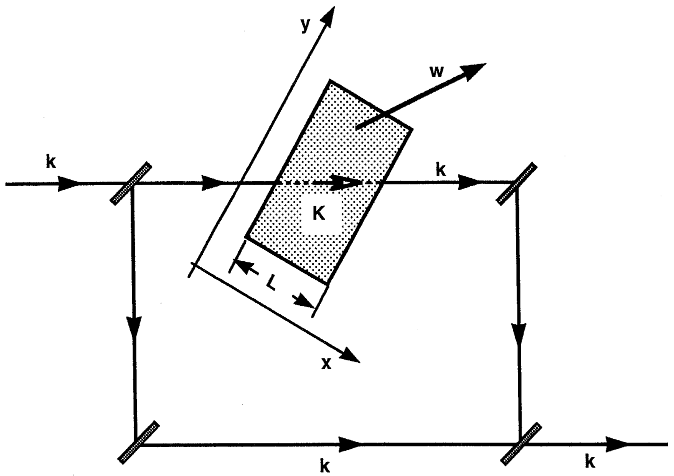
Magnetic noise fields





M.Baron, H.Rauch, M.Suda, J.Opt.B5 (2003) S244

Neutron Fizeau effect



$$n(\vec{k}) = \frac{K_x}{k_x} = \sqrt{1 - \frac{2mV_0\left(\left|\vec{k}\right|\right)}{\hbar^2 k^2}}$$

$$\Delta\phi = \left\{\sqrt{(1-\alpha)^2 - \beta'} + \alpha - \sqrt{1-\beta}\right\} k_x L$$

$$\Delta\phi = -\frac{\alpha\beta k_x L}{2(1-\alpha)} = -\frac{w_x}{v_x}\left(\frac{V_0}{\varepsilon_x}\right)\frac{kL}{2(1-w_x/v_x)}$$

$$\phi\left(\vec{k}\right) = (K_x - k_x)L$$

$$\phi\left(\vec{k}\right) = \left\{\left[n^2\left(\vec{k}\right)k^2 - k_y{}^2\right] - k_x\right\}L$$

$$\Delta\phi = \phi(\vec{k}') - \phi(\vec{k})$$

$$\beta \equiv V_0 \big/ \left(\hbar^2 k_x{}^2 / 2m\right)$$

Galiilean: $\vec{k}' = \vec{k} - \vec{q} \quad with: \quad \vec{q} = m\vec{\omega}/\hbar$

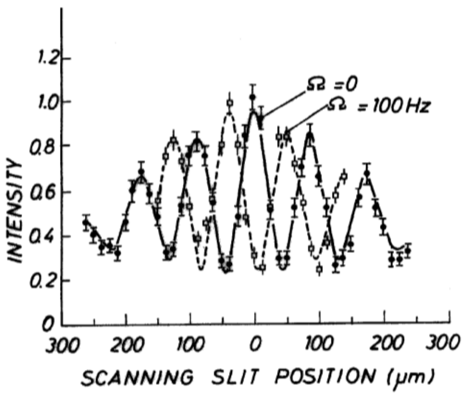
$$\alpha \equiv m w_x / \hbar k_x$$

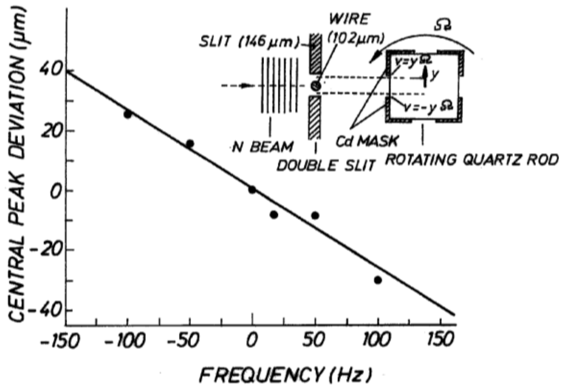
Einsteinian:

$$\vec{k}' = \vec{k} - \left\{(1-\gamma)\frac{\vec{k}\cdot\vec{w}}{w} + \gamma\frac{w}{c}\sqrt{k + \frac{m_0{}^2c^2}{\hbar^2}}\right\}\frac{\vec{w}}{w}$$

Phase shift depends on velocity of boundary surface !!

Neutron Fizeau effect measurements

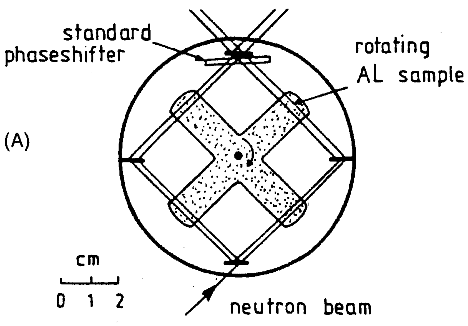




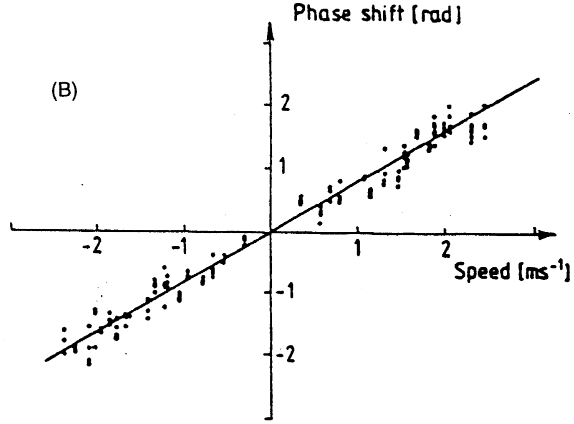
w_x=3.9 cm/s

A.G. Klein et al. Phys.Rev.Lett. 46 (1981) 1551

(A)



(B)

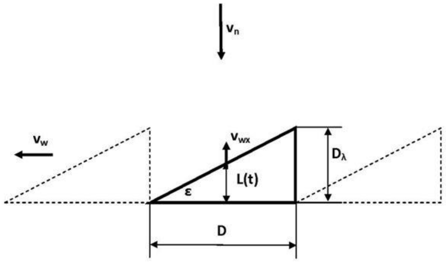


w_x=2.4 m/s

U. Bonse, A. Rumpf Phys.Rev.Lett. 56 (1986) 2441

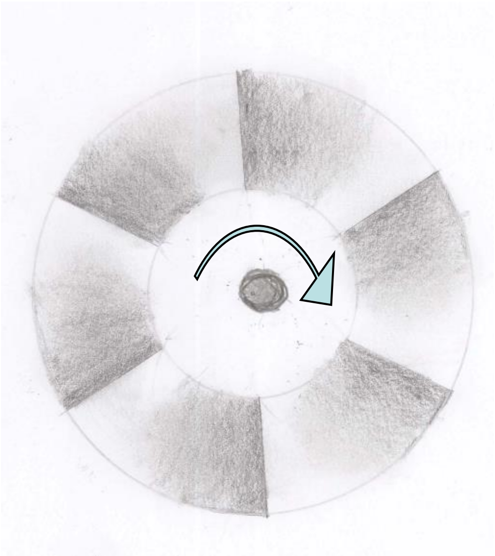
Fizeau-Wheel

$$e^{-iNb\lambda D(t)_c} = e^{-2\pi D(t)/D_\lambda} = e^{-2\pi i v_w t tg\alpha / D_\lambda} = e^{-i\omega t}$$



$$x \equiv L(t) = D_\lambda v_w t / D = v_w t tg\varepsilon; \quad D_\lambda = 2\pi / Nb_c\lambda$$

$$\Delta E = \hbar\omega = 2\pi\hbar v_w tg\alpha / D_\lambda$$



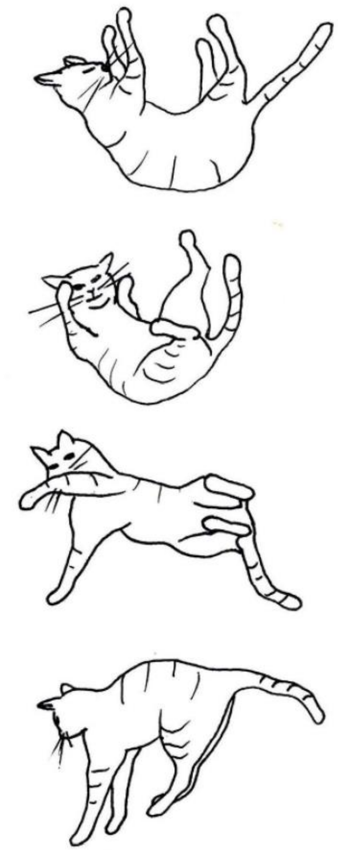
$$e^{i\Delta\Phi(t)} = e^{i\Delta E t/\hbar}$$

Al: D_λ=167.8 µm; α=30º; v_w=10m/s

→ ΔE = 2.47x10^{-11}eV = 24,7 peV

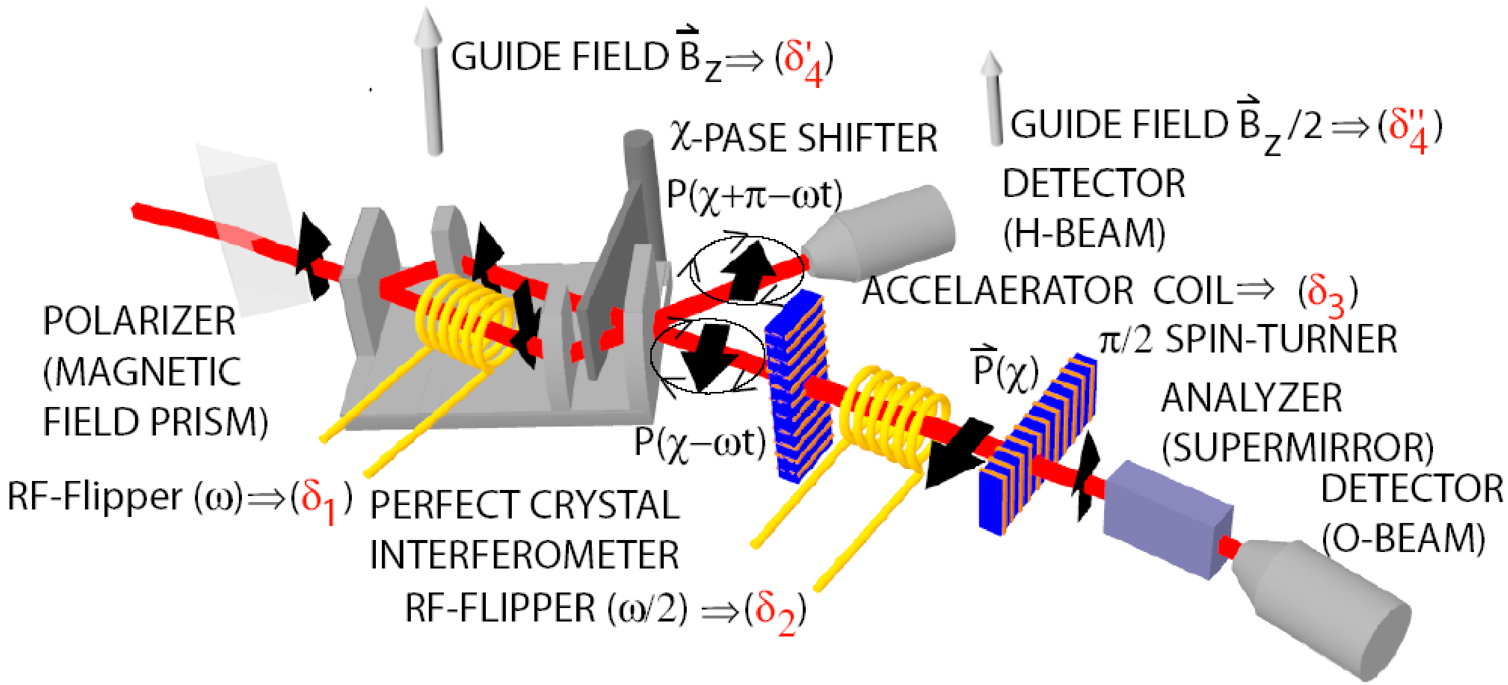
Yuji Hasegawa

A falling cat always lands on its feet.
R. Montgomery, Commun. Math. Phys. **128**, 565 (1990).



- ***Quantum Contextuality and Kochen-Specker phenomenon***

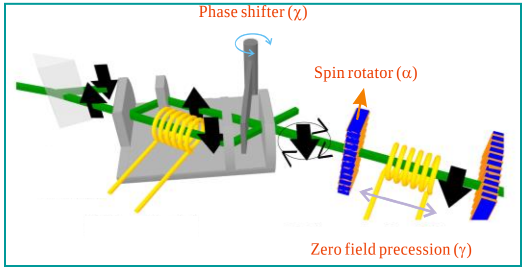
Triply entangled states



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

$$\text{where} \begin{cases} \chi = N\, b_c\, \lambda\, D : \textit{phase shifter} \\ \alpha = \Delta\omega_L\, t : \textit{spin rotator} \\ \gamma = \omega_r\, t : \textit{zero field precession} \end{cases}$$

Mermin`s Inequality: Measurements



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

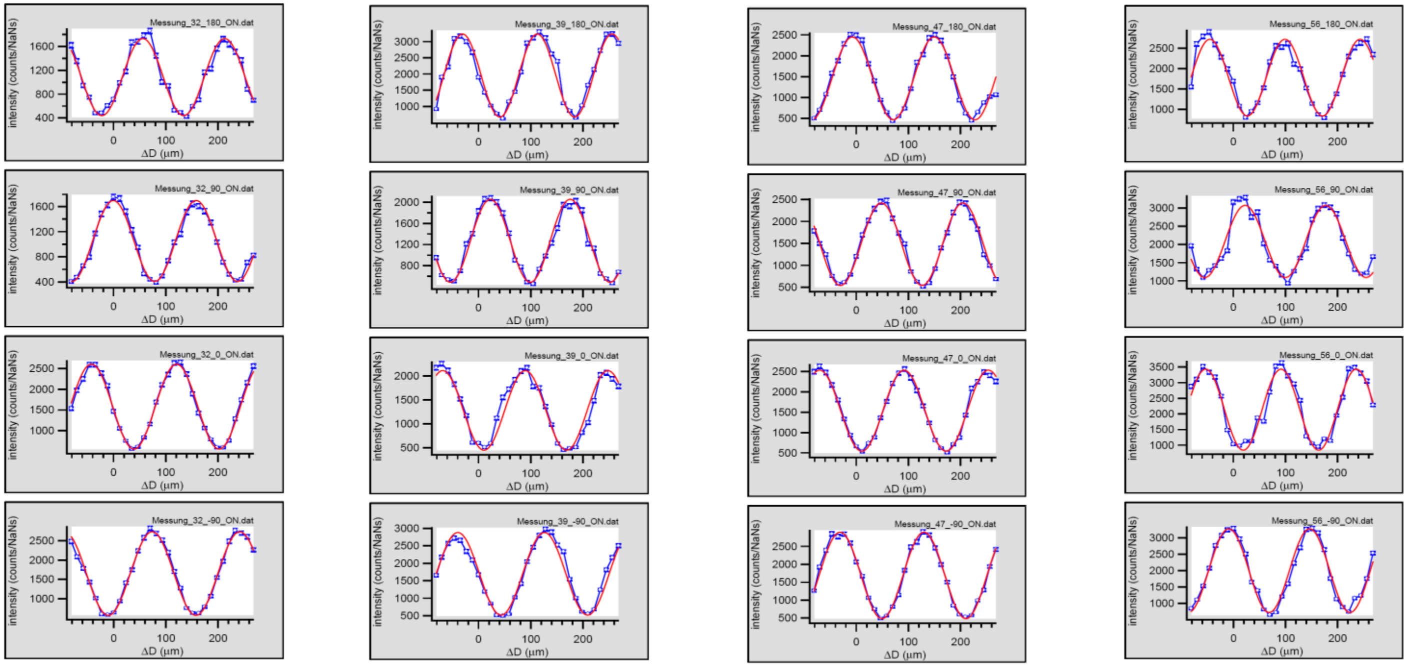
where
$$\begin{cases} \chi = N\, b_c\, \lambda\, D : \textit{phase shifter} \\ \alpha = \Delta\omega_L\, t \quad : \textit{spin rotator} \\ \gamma = \omega_r\, t \quad : \textit{zero field precession} \end{cases}$$

α=0

α=π/2

α=π

α=3π/2



γ=0 γ=π/2 γ=π γ=3π/2

Y. Hasegawa, R. Loidl, G. Badurek S. Sponar, H. Rauch, Phys.Rev.Lett. 103 (2009) 040403

Compton frequency

$$\nu_c = \frac{c}{\lambda_c} = \frac{mc^2}{h}$$

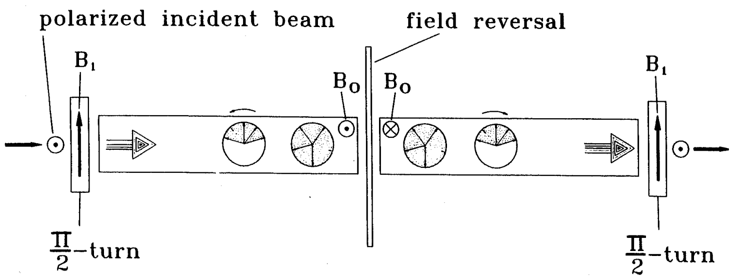
as an internal clock ?

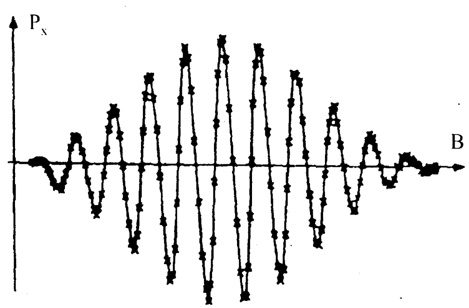
initiated by: H. Müller, A. Peters, S. Chu, Nature 463 (2010) 926

Larmor interferometry

static:

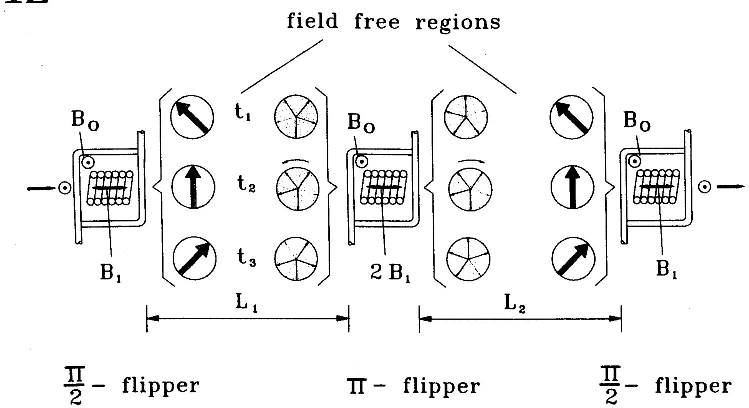
$$\omega_L = \frac{2\mu B_0}{\hbar} \approx 1MHz$$

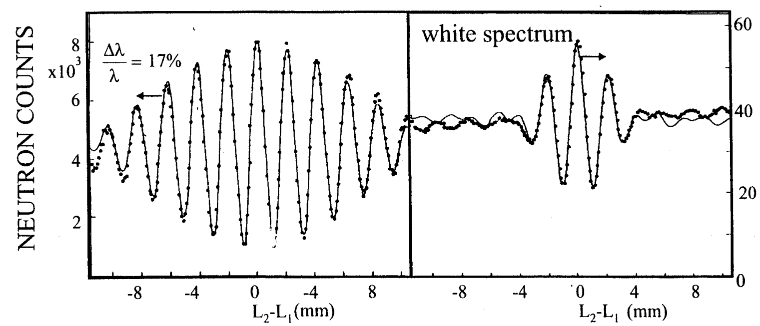




F. Mezei, Z. Physik 255 (1972) 146

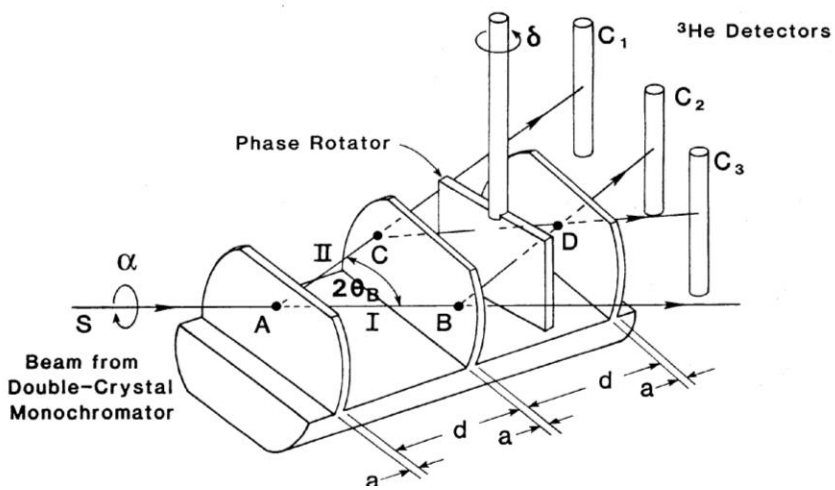
time dependent:

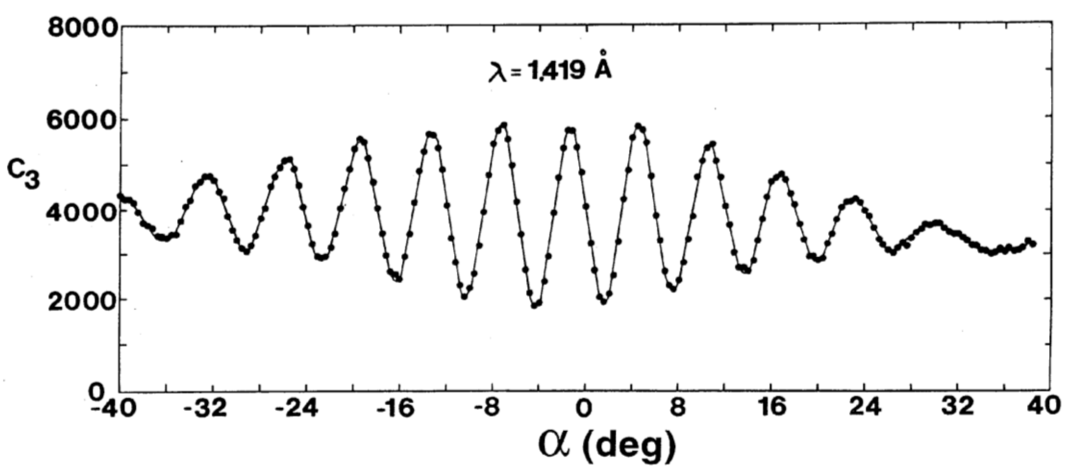




R. Gähler, Golub, J.Phys. France 49 (1988) 1195

COW-Experiment (Colella, Overhauser, Werner)





$$E_o = \frac{\hbar^2 k_o^2}{2m} = \frac{\hbar^2 k^2}{2m} + mgH(\alpha)$$

E_0= 20 meV; mgH ~ 1.003 neV

$$\Delta k = (k - k_o) \cong -\frac{m^2 gH}{\hbar^2 k_o} \sin\alpha$$

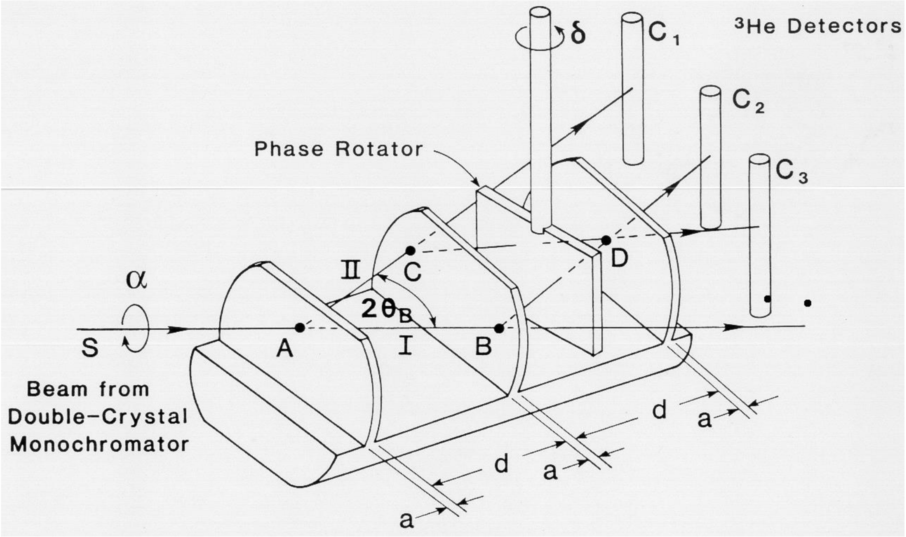
$$\Delta\Phi_{cow} = \Phi_{II} - \Phi_I = \Delta k \cdot S$$

$$\Delta\Phi_{cow} = -2\pi\lambda \frac{m^2}{h^2} gA_o \sin\alpha$$

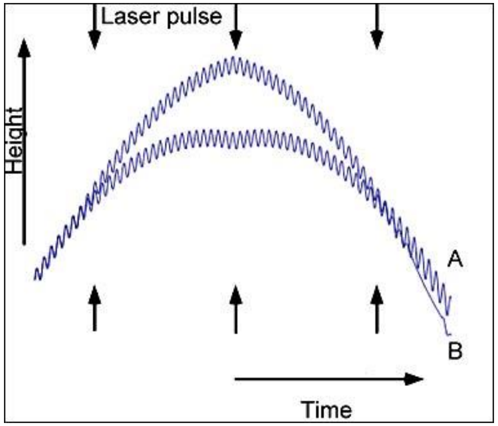
R. Colella, A.W. Overhauser, S.A. Werner, Phys.Rev.Lett. 34 (1974) 1472

Use of Compton Frequency

$$\lambda_C = h/mc \longrightarrow \omega_C = \frac{mc^2}{\hbar} \approx 10^{25}\,Hz$$



Collela R., Overhauser A.W., Werner S.A. Phys.Rev.Lett. 34 (1975) 1053



Peters A., Chung K.Y., Chu S. Nature 400 (1999) 849

Müller H., Peters A., Chu S. Nature 463 (2010) 926

Gravity phase shift

classical motion

$$L_{cl} = \frac{GMm}{r_\oplus} - mgz + \frac{1}{2} m\dot{z}^2$$

$$g = GM / r_\oplus^2 \quad and \quad r = r_\oplus + z$$

$$\varphi = \oint k.ds$$

$$\frac{\hbar^2 k^2}{2m} + mgz = \frac{\hbar^2 k_0^2}{2m}$$

$$\varphi = -2\pi\lambda \frac{m^2}{h^2} g A_0 \sin\alpha$$

Schwarzschild metric for motion

$$L_{gr} = -mc^2 + \frac{GMm}{r_\oplus} - mgz + \frac{1}{2} m\dot{z}^2 + \varnothing\left(\frac{1}{c^2}\right)$$

$$g = GM / r_\oplus^2 \quad and \quad r = r_\oplus + z$$

$$\tau = \tau_0 (1 + \Delta U / mc^2)$$

$$(\Delta U = -mgH)$$

$$\varphi = \frac{1}{\hbar} \oint mc^2 d\tau = \omega_c \oint d\tau$$

$$\Delta\varphi = \frac{mc^2}{\hbar} \frac{\Delta U}{mc^2} \tau_0 = -\frac{mgH}{\hbar} \frac{L}{v} = -2\pi\lambda \frac{m^2}{h^2} g A_0 \sin\alpha$$

Müller H., Peters A., Chu S. Nature 463 (2010) 926

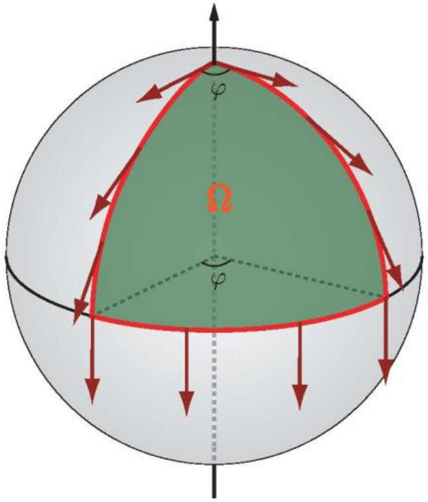
debate with: Wolf P., Blanchhet L., Borde C.J., Raynaud S., Salomon C., Cohen-Tannoudji, Class.Quantum Grav. 28 (2011) 145017

Résumé

- **Advanced post-selection makes quantum experiments better understandable and less mystic.**
- **Quantum physics gives more correlations, entanglements an contextual effects than classical physics.**
- **For the interpretation one should keep in mind that the initial or boundary conditions are also based on statistical measurements of an equally prepared ensemble and, therefore, it does not seem so surprising that only statistical predictions about the outcome of an experiment can be made.**
- **Thus, we do not know everything at the beginning so we also do not know everything at the end.**

Thank You

- *Geometrical Phases*



Geometric Phase

Geometric Phase

Berry Phase (adiabatic & cyclic evolution)

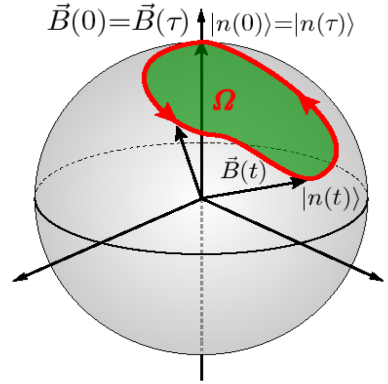
[Berry; Proc.R.S.Lond. A 392, 45 (1984)]

$$|\psi(t)\rangle = e^{-i\phi_d} e^{i\phi_g} |n(R(t))\rangle$$

$$\phi_d(t) = \frac{1}{\;} \int_0^t dt' E_n(t')$$

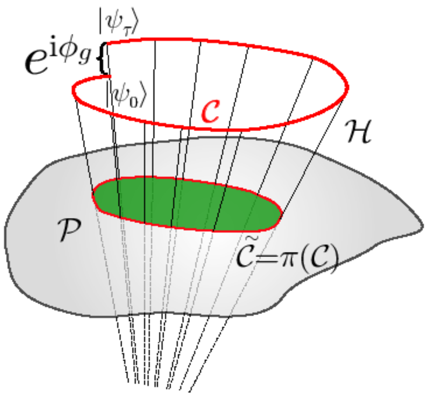
$$\phi_g = -\frac{1}{2}\,\Omega$$

(for 2-level systems)



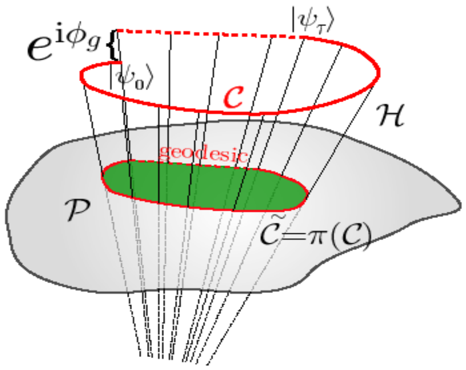
Non-adiabatic evolution

[Aharonov & Anandan, PRL 58, 1593 (1987)

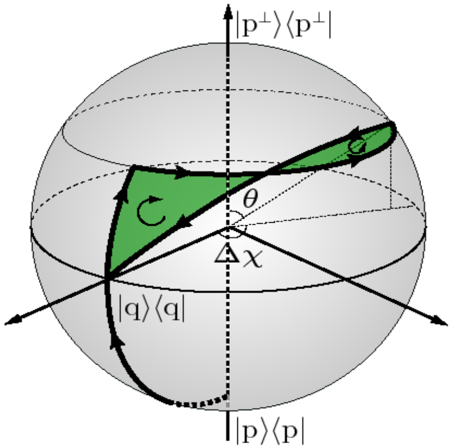


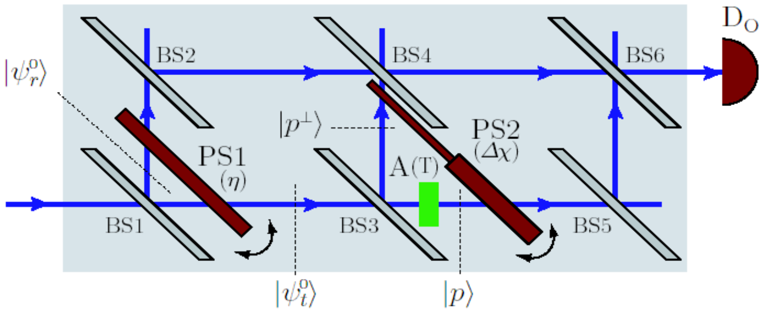
Non-adiabatic & non-cyclic evolution

[Samuel & Bhandari, PRL 60, 2339 (1988)]



Non-adiabatic & Non-cyclic Phase





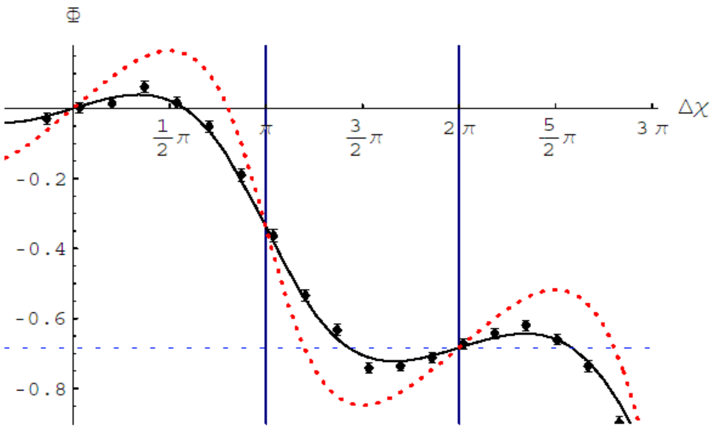
$$\Phi \equiv \arg\langle\psi_r'|\psi_t'\rangle = \frac{\chi_1+\chi_2}{2} - \arctan\left[\tan\frac{\Delta\chi}{2}\left(\frac{1-\sqrt{T}}{1+\sqrt{T}}\right)\right]$$

$$\Phi_g \equiv \Phi - \Phi_d = \Phi$$

Cancelling dynamical phase, if

$$\Phi_d = \frac{\chi_1 + T\chi_2}{1+T} = 0$$

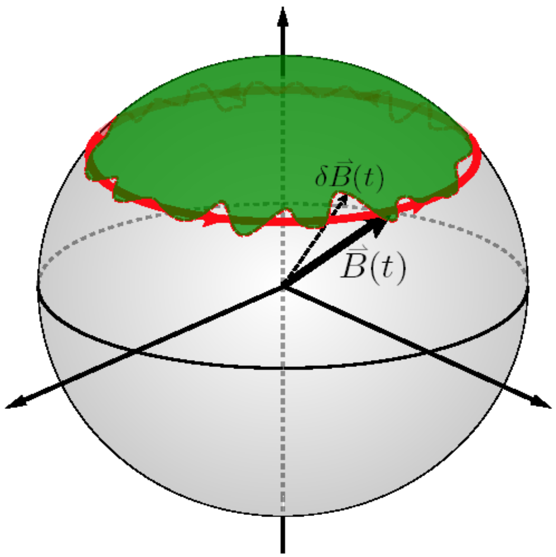
Results:

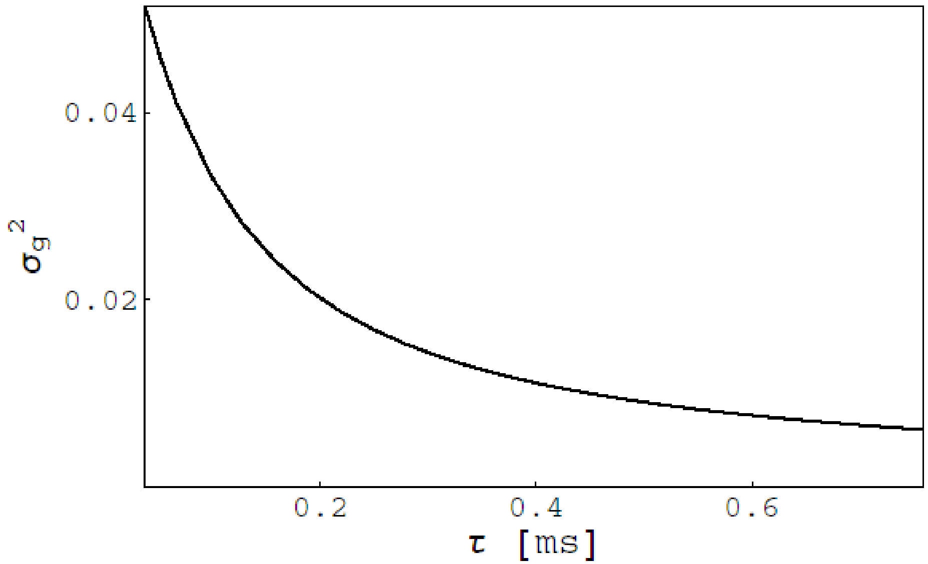


S. Filipp, Y. Hasegawa, R. Loidl and H. Rauch, Phys.Rev. A72 (2005) 021602

Dephasing - Decoherencing

G. De Chiara and G.M. Palma, PRL 91, 090404 (2003)
R.S. Whitney, Y. Gefer, Phys.Rev.Lett. 90(2003)190402

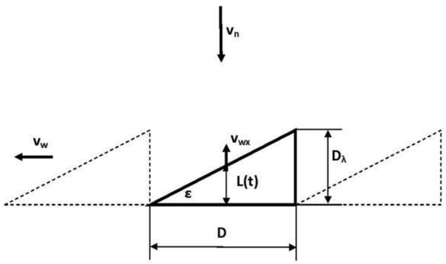




Variance of geometric phase (σ_g^2) tends to 0 for increasing time of evolution in a magnetic field.

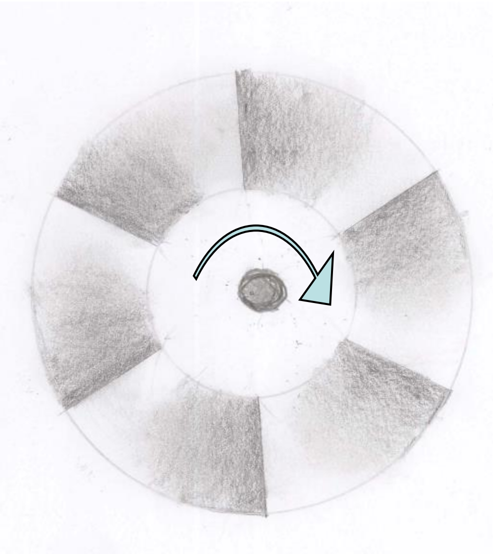
Fizeau-Wheel

$$\Delta\Phi_{Fizeau} = -\frac{\alpha\beta k_x L}{2(1-\alpha)}$$



$$x \equiv L(t) = D_\lambda v_w t / D = v_w t tg\varepsilon; \quad D_\lambda = 2\pi / Nb_c\lambda$$

$$\Delta\Phi(t) = \frac{v_w tg\alpha}{v_n}\left(\frac{2V_0}{mv_n^2 tg^2\alpha}\right)\frac{mv_n v_w tg\alpha}{2\hbar\left(1-\frac{v_w tg\alpha}{v_n}\right)}.t = \frac{V_0 v_w^2}{\hbar v_n(v_n - v_w tg\alpha)}.t$$



$$e^{i\Delta\Phi(t)} = e^{i\Delta E t/\hbar}$$

$$\Delta E = \hbar\omega = \frac{V_0 v_w^2}{v_n(v_n - v_w tg\varepsilon)} \approx V_0 \frac{v_w^2}{v_n^2}$$

Al: V_0=5.415x10^{-8} eV; v_n=1000m/s; v_w=10m/s

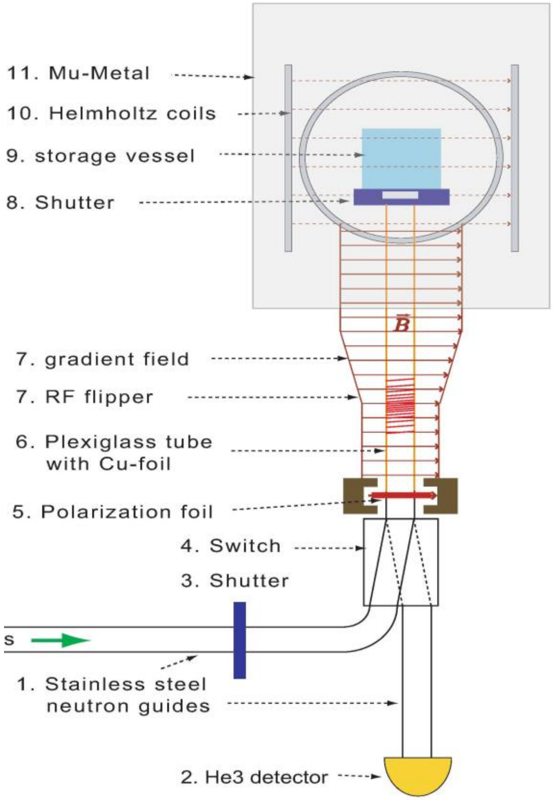
→ ΔE = 5.4x10^{-12}eV = 5.4 peV

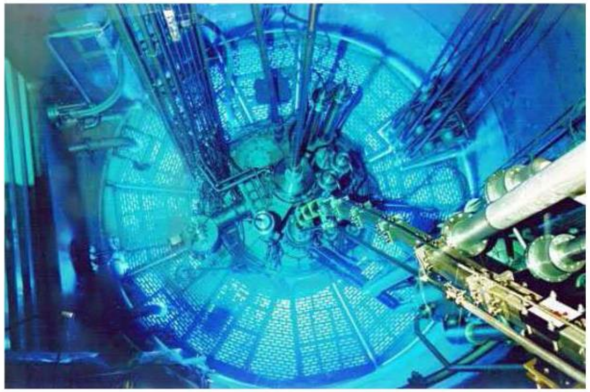
Ultra-cold neutrons

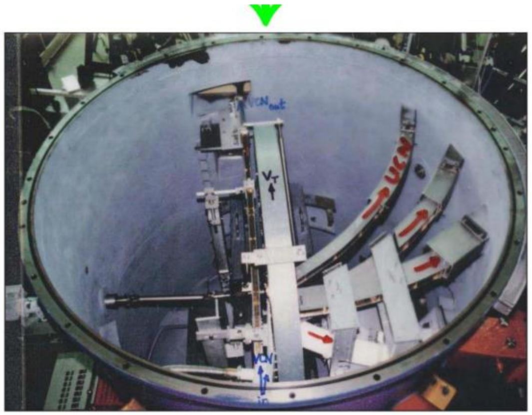
- polarized Ultra Cold Neutrons (UCN's)
- low velocity $\approx 5m/s$ $(10^{-7}eV, \approx mK)$
- reflection at material wall - potential barrier $(\approx 10^{-7}eV)$
- neutron bottle

- wrap coils around for magnetic field

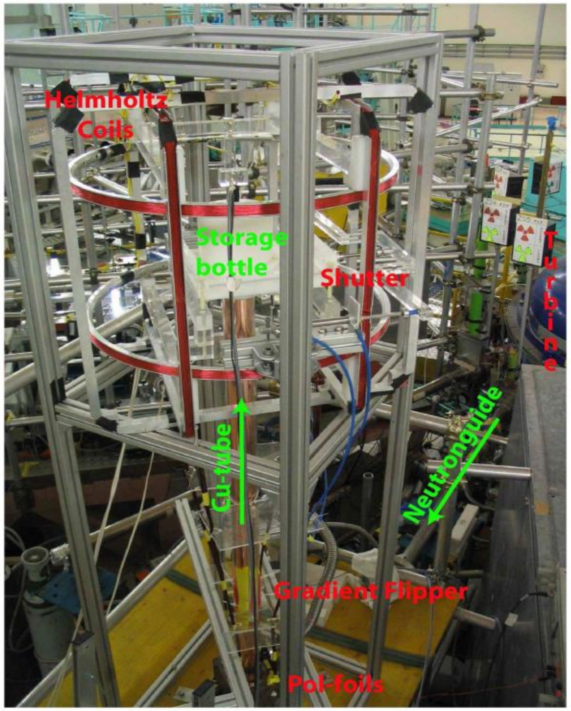
Ultra-cold neutrons at ILL







Experimental set-up

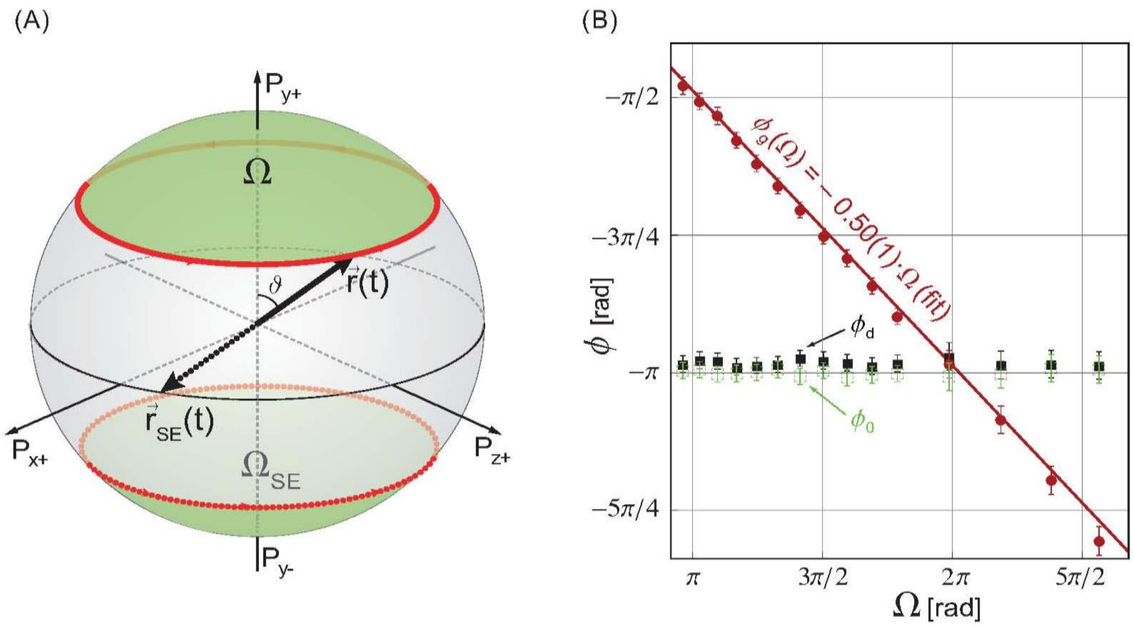


S. Filipp, J. Klepp, Y. Hasegawa, Ch. Plonka, P. Geltenbort, U. Schmidt, H. Rauch, Phys.Rev.Lett.102 (2009) 030404

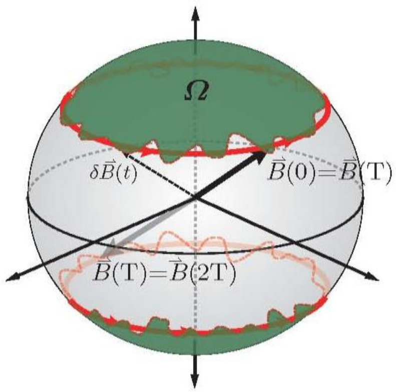
Compensation of the dynamical phase

Compensation of the dynamical phase

ϕ_g for different ϑ, i. e. x-offset fields
$(\omega = 2\pi/T \approx 30 \text{ rads}^{-1} \mathrel{\widehat{=}} \text{T} = 200 \text{ ms},\ \omega_L = 1832 \text{ rads}^{-1} \mathrel{\widehat{=}} \text{B} = 10\ \mu\text{T})$:



Compensation in the case of noise fields

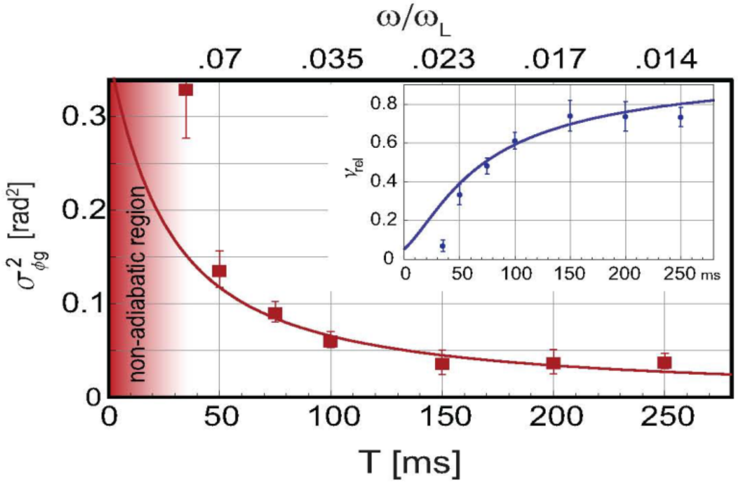


Spin-Echo Setup:

- One cycle: $\psi(\tau) = e^{i(\phi_d+\phi_g)}\psi(0)$
- Spin Echo: $\phi_d = 0$ (spin first in the positive and then in negative eigenstate of the magnetic field Hamiltonian).
- Geometric phase $\phi_g(2\tau) = 2\phi_g(\tau)$

Rubustness of the geometric phase

- $\phi_g^0 = 2.58\ \text{rads}^{-1}$, $B = 10\ \mu\text{T}(1832\ \text{rad/s})$
- noise rms $\sigma_P = 2\ \mu\text{T}(366\ \text{rad/s})$, bandwidth $\Gamma = 100\ \text{rad/s}$
- $\overline{\phi}_g$: averaged over 300 cycles
- State tomography (6 cycles)
- measure degree of polarisation relative to noise-free evolution $\nu_{rel} = e^{-8\sigma^2_{\phi g}}/e^{-8\sigma^2_{g0}}$
- $\langle\overline{\phi}_g\rangle - \phi_g^0 = 0.0(1)$ rad

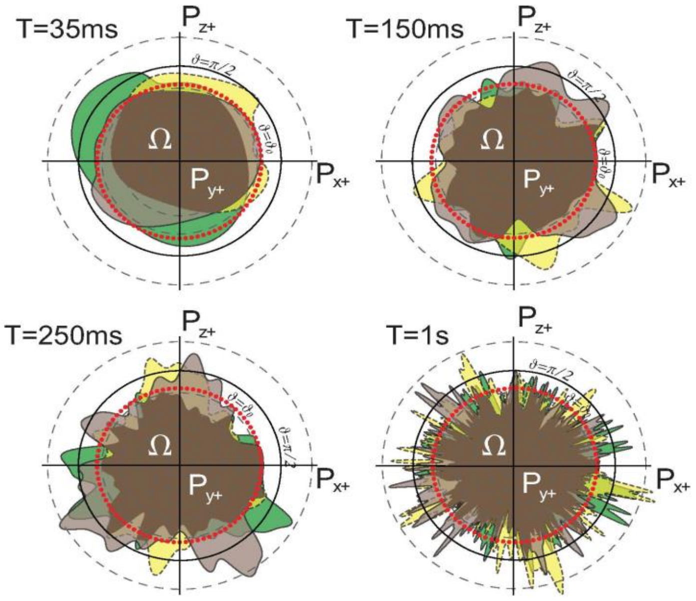


F. Filipp, J. Klepp, Y. Hasegawa, Ch. Plonka, P. Geltenbort, U. Schmidt, H. Rauch, Phys.Rev.Lett.102 (2009) 030404

Visualisation of the robustness of geometric phases

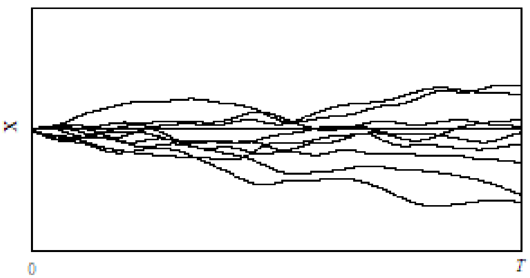
- Stereographic plots of sample noise realizations (simulation):

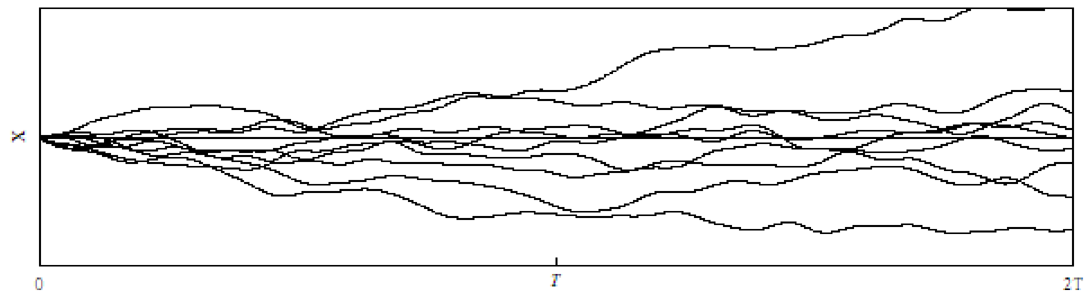
- ✘ effective frequency changes
- ✘ less fluctuations in enclosed area for longer T
- ✘ less dispersion of ϕ_g



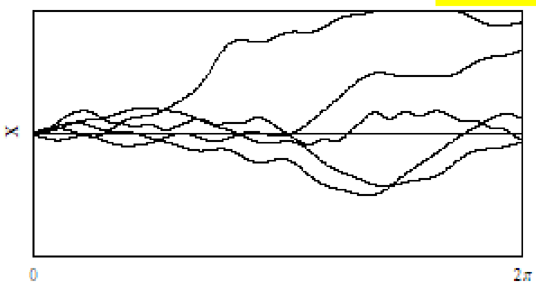
Stability calculations

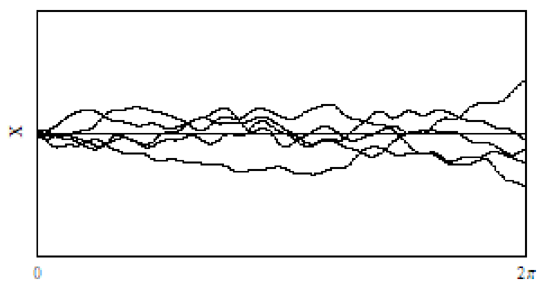
Dynamical Phase ($\int dt$):

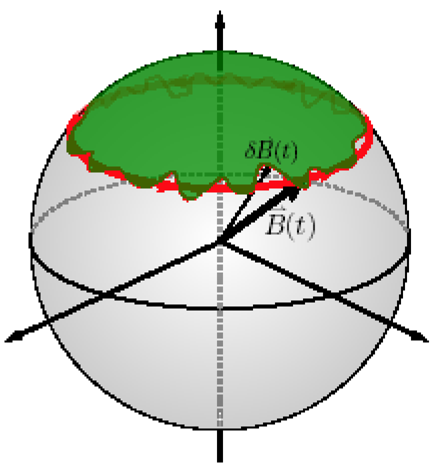


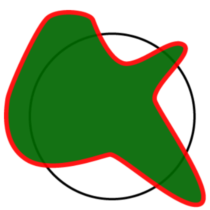


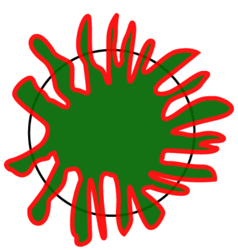
Geometric Phase ($\int d\Omega$):











Wave-Latice Interaction