Gravitation-induced quantum interference for neutrons

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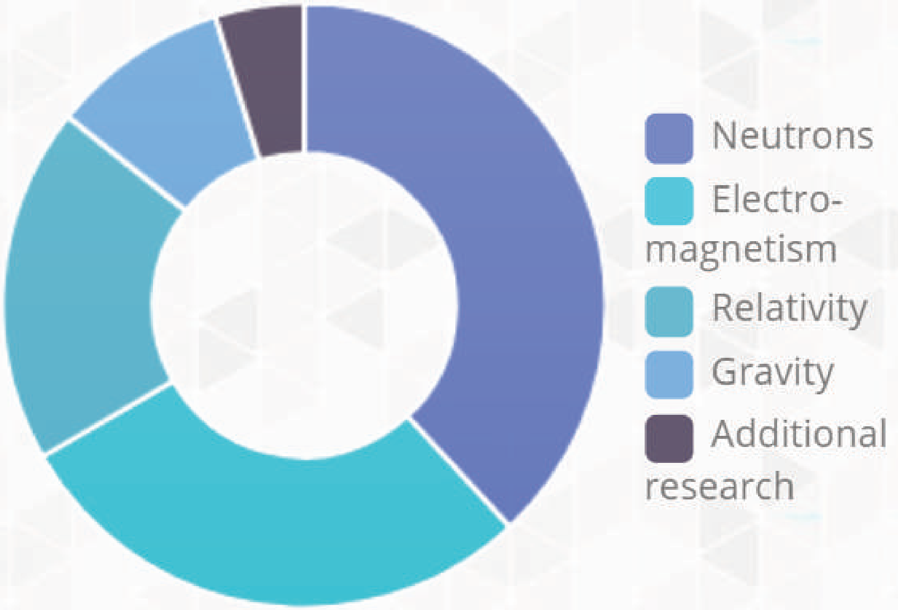
Outline

- Introduction
- Principle
- Past measurements
- Future measurement
- Closure

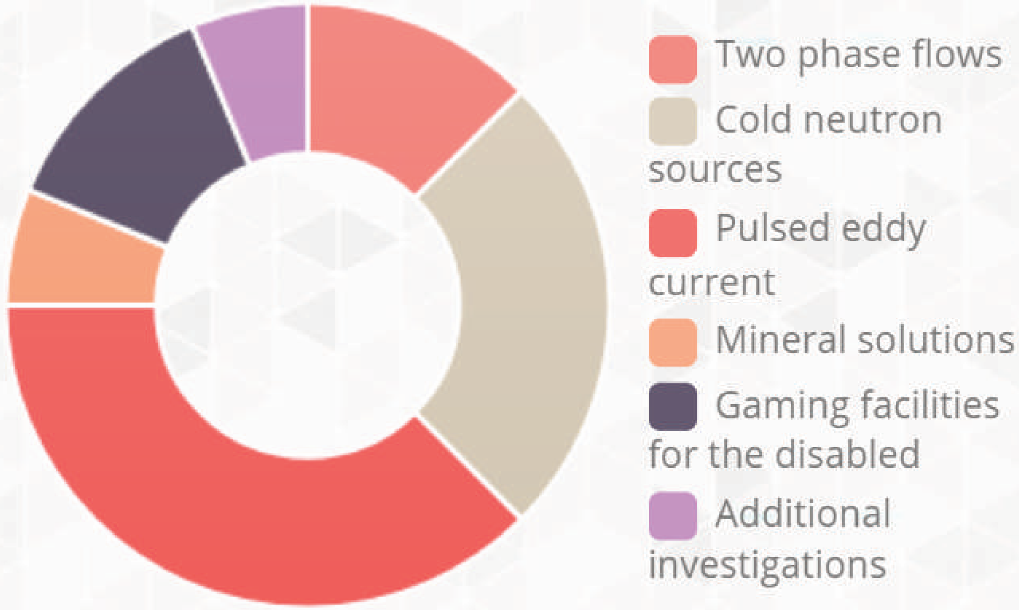
Introduction

- Established: April 1, 1997
- 2 Employees
- Turnover ~100kEuro
- Consultancy and research

Research



Investigations

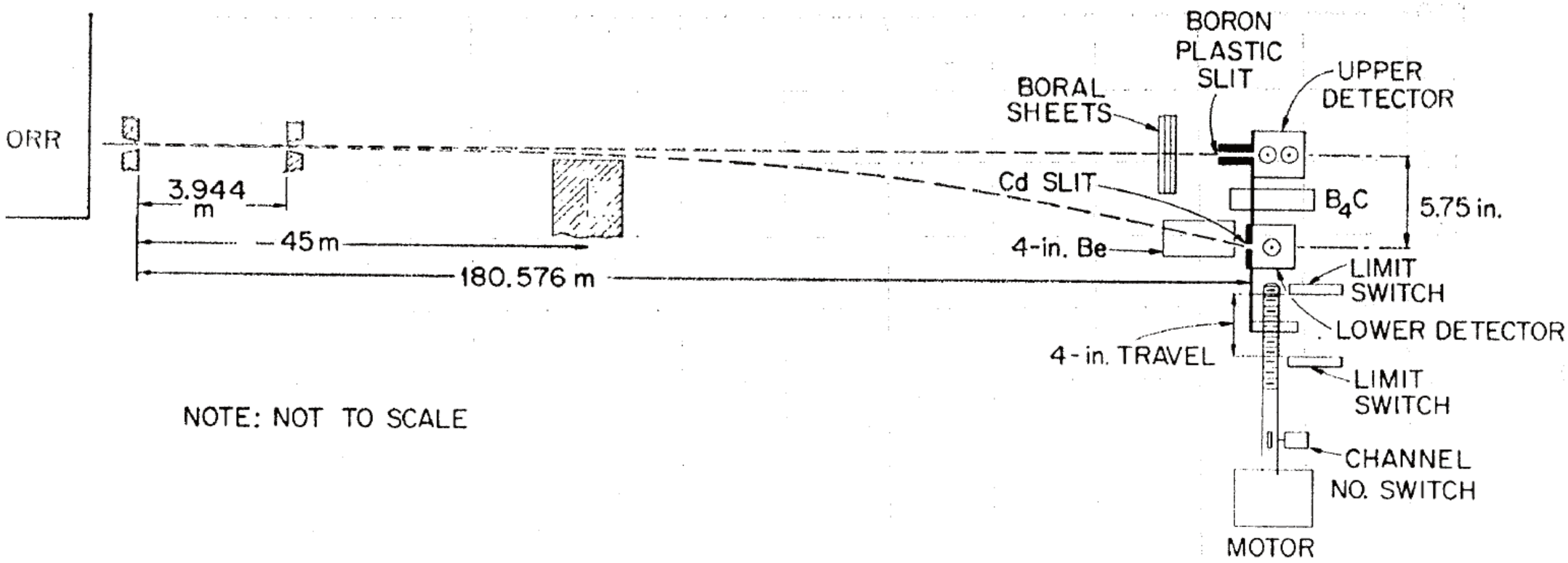


Principle

- Neutrons fall down
- Coherence theory
- Interaction of neutron with magnetic field
- Propagation of polarization
- Spin echo

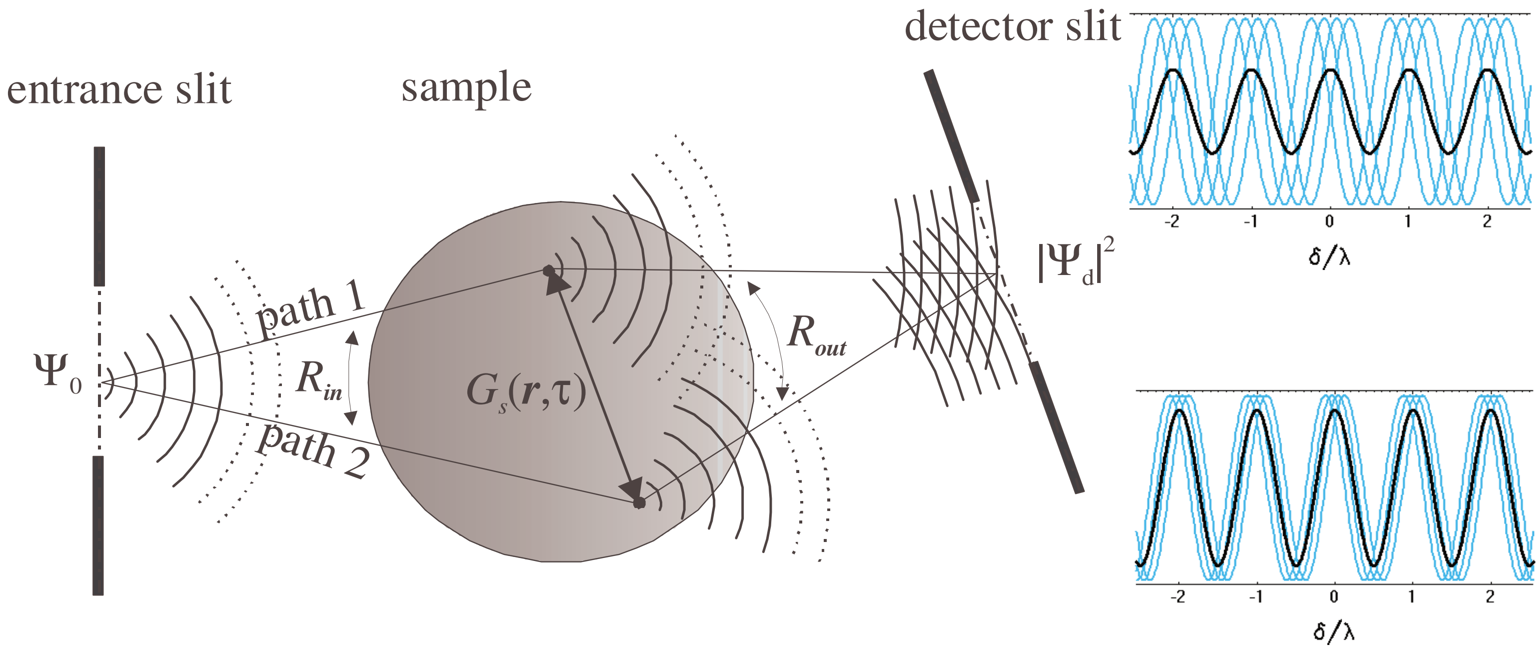
Principle

- Neutrons fall down: McReynolds 1951, Dabbs 1965



Principle

- Coherence theory: Scattering as coherence phenomena, Gähler et al. (1998)



Principle

- Coherence theory: Mutual coherence function (Mandel, 1965)

$$\Gamma(\mathbf{r}_1,\mathbf{r}_2,\tau)=\left\langle \psi^*(\mathbf{r}_1,t)\psi(\mathbf{r}_2,t+\tau)\right\rangle_t$$

$$\Gamma(\mathbf{r}_1,\mathbf{r}_1,0)=\left\langle \psi^*(\mathbf{r}_1,t)\psi(\mathbf{r}_1,t+0)\right\rangle_t = J(\mathbf{r}_1)$$

$$I_d = 2v_p \int_{A_d} J(\mathbf{r}_d) d^2 r_d$$

Principle

- Interaction of neutron with magnetic field

  The Schrödinger equation:

$$i\hbar\frac{\partial}{\partial t}\Psi(\mathbf{r},t)=-\frac{\hbar^2}{2m}\nabla^2\Psi(\mathbf{r},t)+V(\mathbf{r},t)\Psi(\mathbf{r},t)$$

$$V(\mathbf{r})=-\boldsymbol{\mu}_n\cdot\mathbf{B}$$

  - potential energy due to spin: Zeeman energy
  - include spinor description
  - for the moment we omit interaction with material

Principle

- Interaction of neutron with magnetic field

The potential energy of the neutron in a magnetic field and resulting kinetic energy are

$$E_{\text{pot}} = \hbar\omega_{\text{z}} = \pm\mu_n B; \qquad E_{\text{kin}}^{\pm} = E_0 \mp \mu_n B; \qquad k^{\pm} = k_0 \mp \Delta k,$$

with

$$\Delta k = \frac{m}{\hbar^2 k_0}\mu_n B = \frac{m\omega_z}{\hbar k_0} = \frac{\omega_z}{v_0} = \frac{-m\gamma_n}{2h}\lambda_0 B.$$

resulting in the Schrödinger equation:

$$i\hbar\frac{\partial\Psi}{\partial t} = -\frac{\hbar^2}{2m}\frac{\partial^2\Psi}{\partial y^2} + \begin{bmatrix} \mu_n B & 0 \\ 0 & -\mu_n B \end{bmatrix}\Psi$$

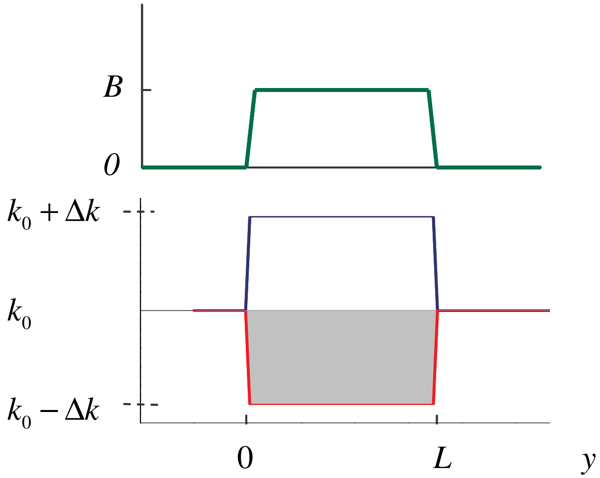
Principle

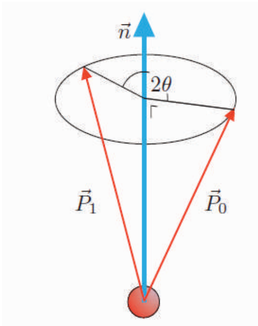
- Coherence function becomes coherence matrix

$$\widehat{\Gamma}(\vec{r}_1, \vec{r}_2, \tau) = \left\langle \begin{pmatrix} \Psi^+(\vec{r}_2, t+\tau) \\ \Psi^-(\vec{r}_2, t+\tau) \end{pmatrix} \begin{pmatrix} \Psi^+(\vec{r}_1, t)^* & \Psi^-(\vec{r}_1, t)^* \end{pmatrix} \right\rangle_t ,$$

Principle

- Interaction of neutron with magnetic field





Interpretation: the neutron spin (expect.value) precesses by an angle $2\theta = 2\Delta kL = -m\gamma_n\lambda_0 BL/h$ around the field direction, being the integration of the wave-number difference between the plus and minus wave function integrated over L

$$p_x(L) = \langle \hat{\sigma}_x \rangle = ab^* + a^*b = \exp(-2i\Delta kL) + \exp(2i\Delta kL) = \cos 2\Delta kL$$

$$p_y(L) = \langle \hat{\sigma}_y \rangle = i(ab^* - a^*b) = i(\exp(-2i\Delta kL) - \exp(2i\Delta kL)) = \sin 2\Delta kL$$

Principle

- Propagation of polarization

Mezei (1980): Polarisation is coherence between spinstates

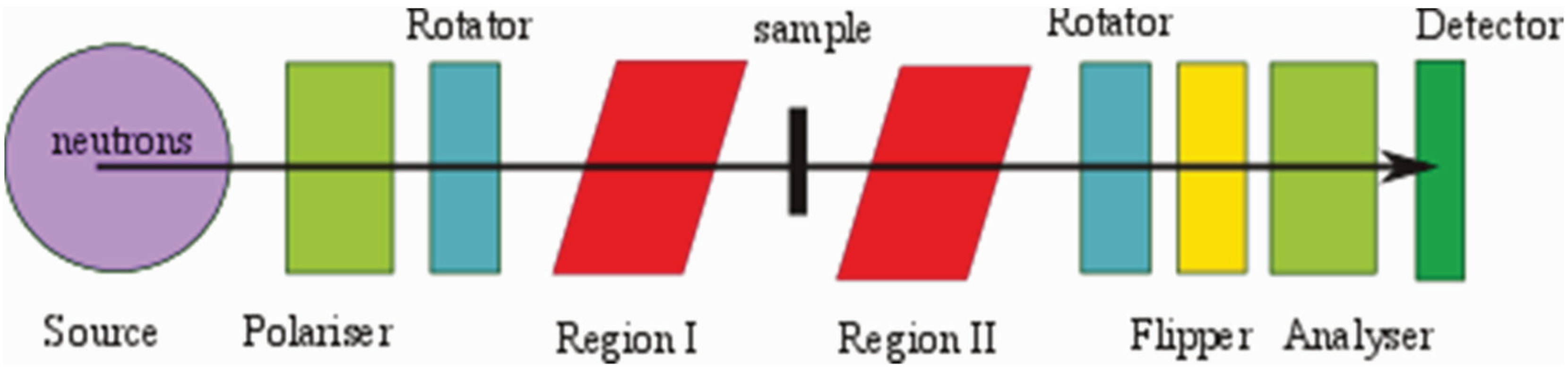
$$P_j(\vec{r}) = \frac{\left\langle \begin{pmatrix} \Psi^+(\vec{r},t)^* & \Psi^-(\vec{r},t)^* \end{pmatrix} \hat{\sigma}_j \begin{pmatrix} \Psi^+(\vec{r},t) \\ \Psi^-(\vec{r},t) \end{pmatrix} \right\rangle_t}{\langle \Psi^+(\vec{r},t)\Psi^+(\vec{r},t)^* \rangle_t + \langle \Psi^-(\vec{r},t)\Psi^-(\vec{r},t)^* \rangle_t},$$

$$\hat{\Gamma}(\vec{r}_1,\vec{r}_2,\tau) = \left\langle \begin{pmatrix} \Psi^+(\vec{r}_2,t+\tau) \\ \Psi^-(\vec{r}_2,t+\tau) \end{pmatrix} \begin{pmatrix} \Psi^+(\vec{r}_1,t)^* & \Psi^-(\vec{r}_1,t)^* \end{pmatrix} \right\rangle_t,$$

$$P_j(\vec{r}) = \frac{\mathrm{Tr}(\hat{\Gamma}(\vec{r},\vec{r},0)\hat{\sigma}_j)}{\mathrm{Tr}(\hat{\Gamma}(\vec{r},\vec{r},0))},$$

Principle to practice

- Propagation of polarization



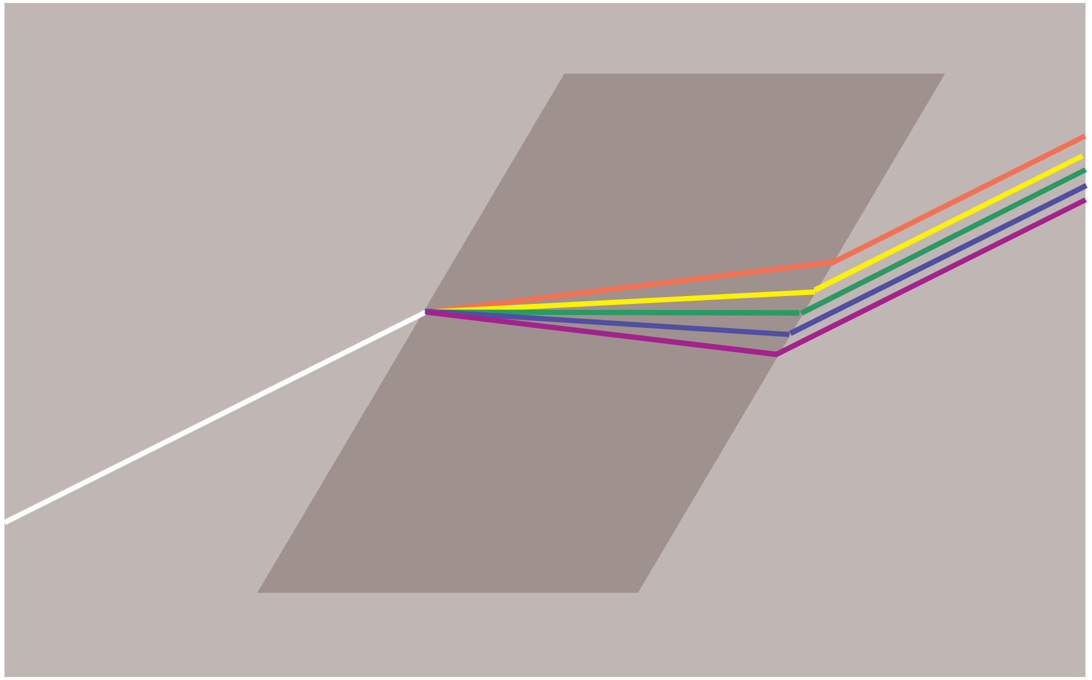
$$J_s^{(2)}(\vec{r}_d) = \frac{\left|\vec{J}_n(\vec{r}_d) + \vec{J}_f(\vec{r}_d)\right|}{2},$$

$$J_f^{(2)}(\vec{r}_d) = \frac{\left|\vec{J}_n(\vec{r}_d) - \vec{J}_f(\vec{r}_d)\right|}{2}$$

$$P_m^{(2)}(\vec{r}_d) = \frac{J_f^{(2)}(\vec{r}_d)}{J_s^{(2)}(\vec{r}_d)},$$

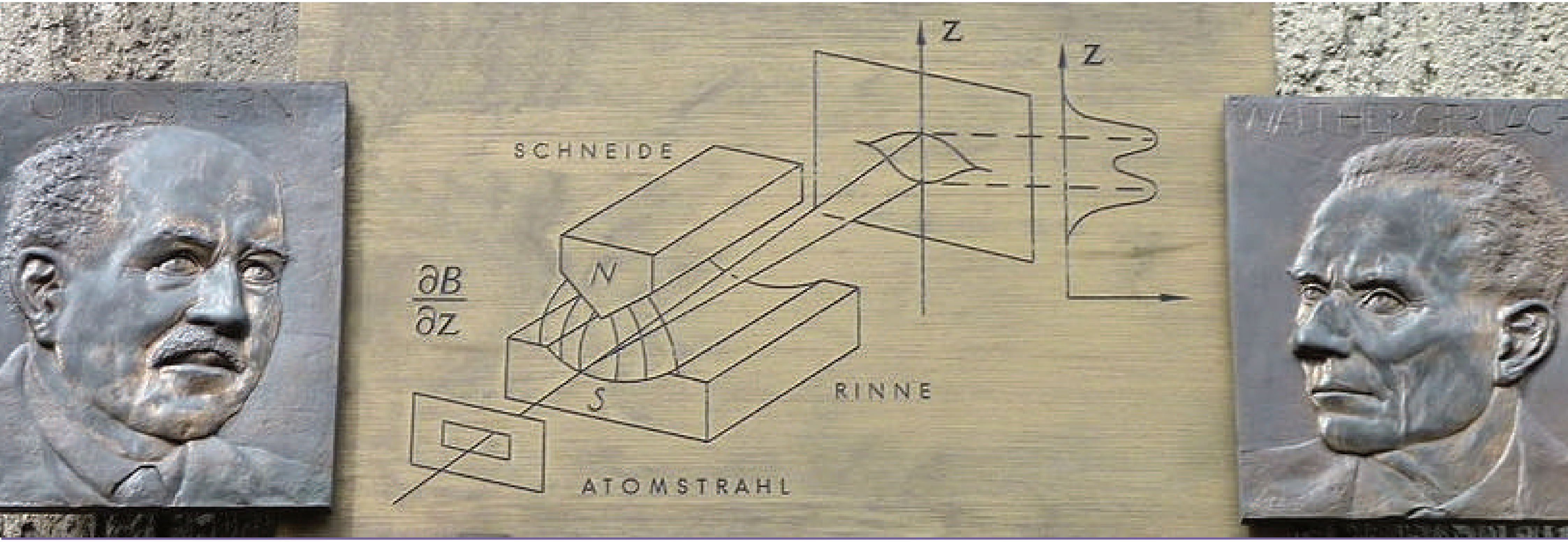
Principle

- Refraction of light



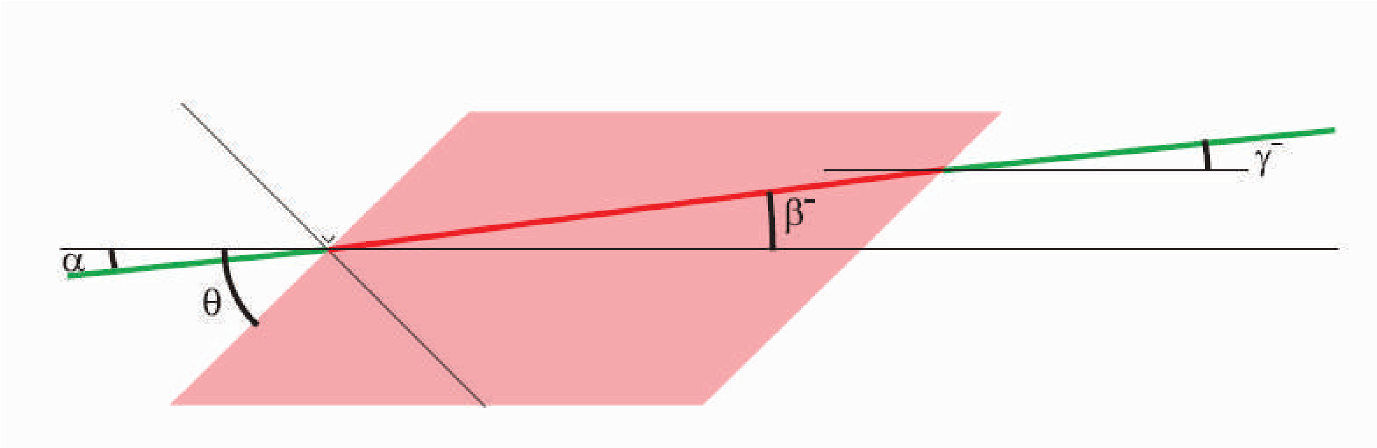
Principle

- Refraction at magnetic boundaries



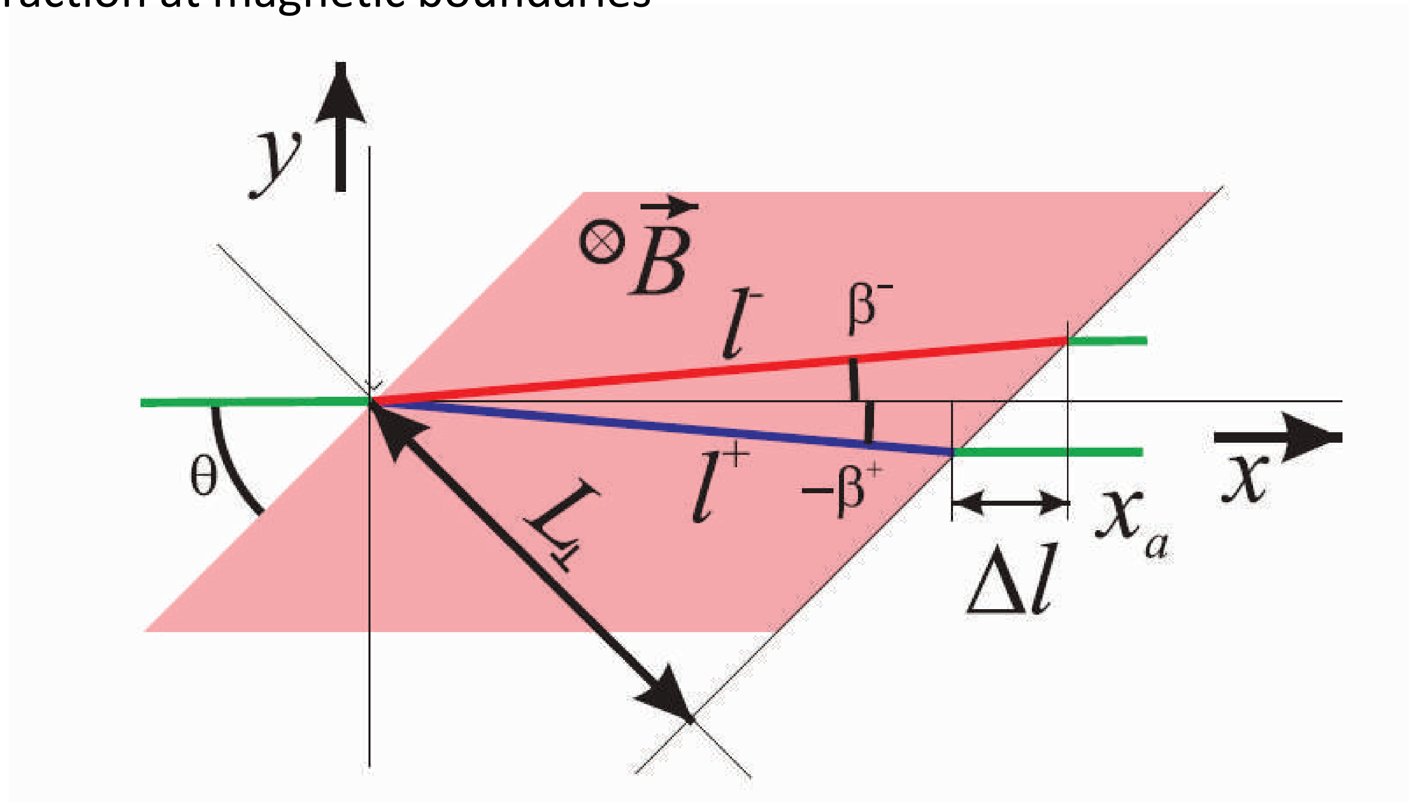
Principle

- Refraction at magnetic boundaries



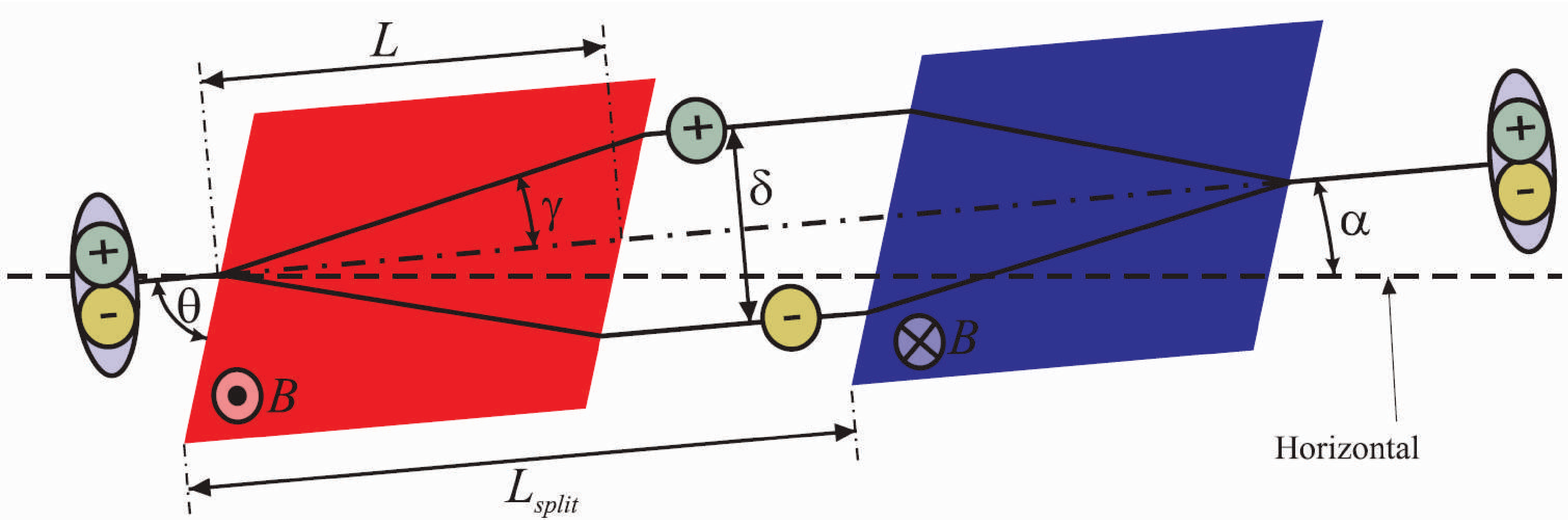
Principle

- Refraction at magnetic boundaries



Principle

- Spin Echo: Interferometer for the two spin states

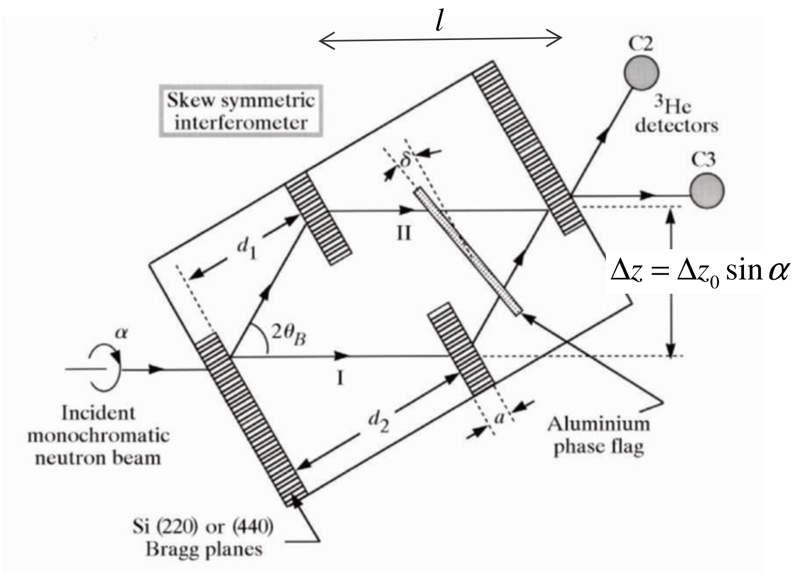


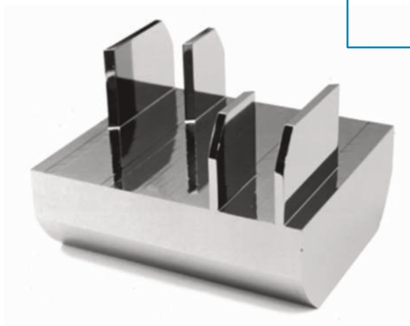
Past measurements

- COW
- De Haan et al.

Past Measurements

- Si single-crystal interferometer (COW experiments)





R. Colella *et al.*, Phys. Rev. Lett. **34** (1975) 1472
K.C. Littrell *et al.*, Acta Cryst. **54** (1998) 563

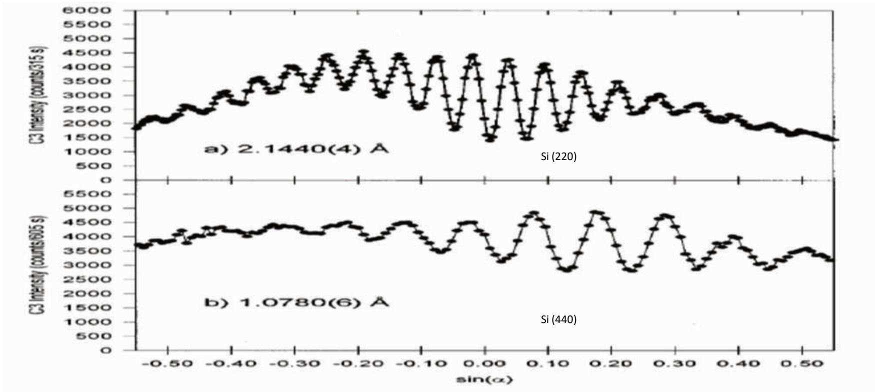
phase difference between both paths:

$$\Delta\phi = k_I l - k_{II} l \propto \Delta k_g l \Delta z$$

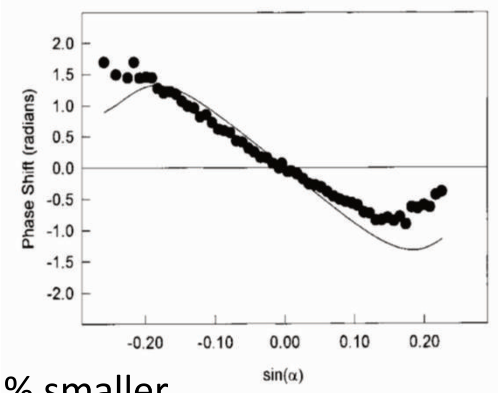
Past Measurements

- Si single-crystal interferometer (COW experiments)

Results: interference signal as a function of extra phase added to both arms for two wavelengths



phase shift $\Delta\phi$ as a function of rotation angle α



some numbers

$E_{220} = 18$ meV

$E_{440} = 70$ meV

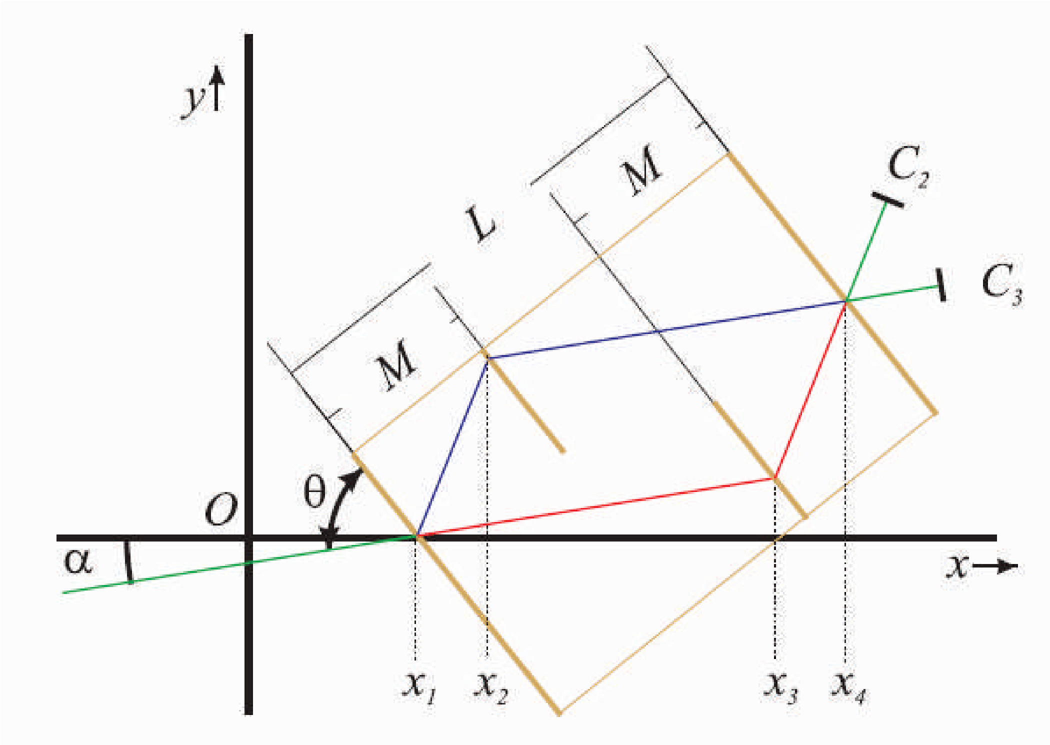
$\Delta z = 18$ mm

$\Delta E_g \approx 2$ neV

Conclusion:
experimental phase shift is 1.0 ± 0.1% smaller, compared with theory, when taking $m_i = m_g$

Past Measurements

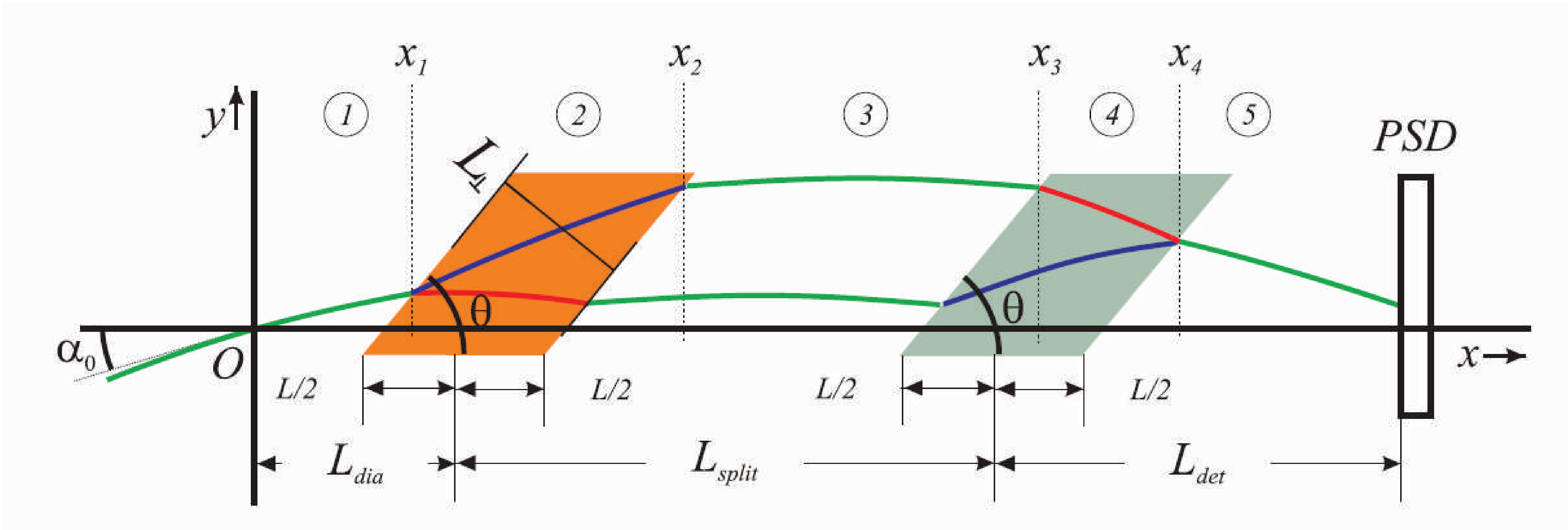
- Si single-crystal interferometer (COW experiments)



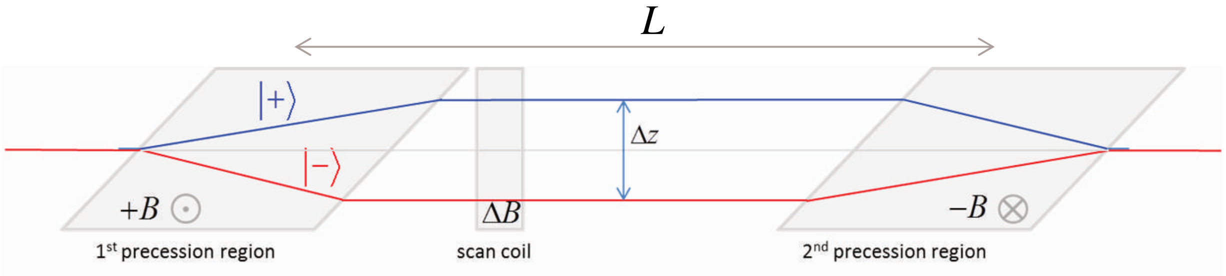
$$\frac{Am^2 g}{\hbar^2 k_0} \cos\alpha (1 - \tan\theta_B \tan\alpha).$$

Conclusion:
experimental phase shift is 1.0 ± 0.1% smaller, compared with theory, when taking $m_i = m_g$

Past Measurements

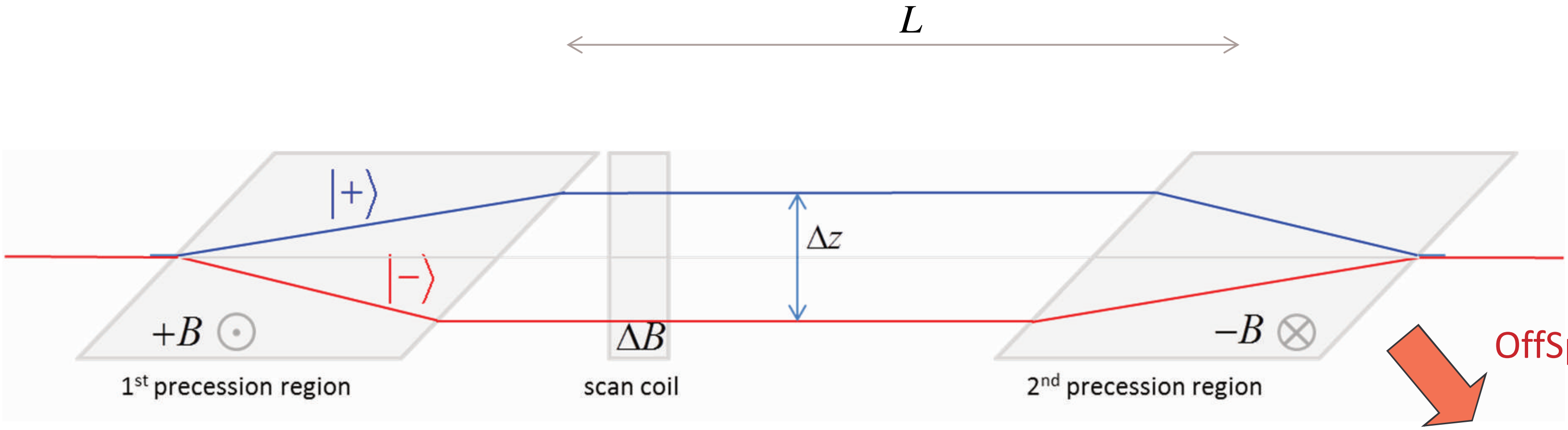


Past Measurements

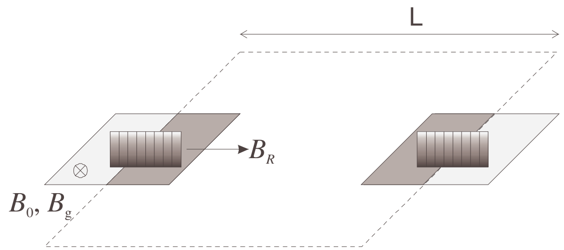


- Offspec is a time-of-flight instrument covering wavelength range $0.2 < \lambda < 1.4$ nm
- The spin-echo polarisation of the recombined neutrons is measured: $P(B,\lambda) = \langle \cos(\phi_L) \rangle$
- with Larmor phase: $\phi_L = \int \left(k^+(x) - k^-(x)\right) dx \propto \Delta k_g L \Delta z$
- extra phase is created by scan coil
- experiments are performed with splitting both in horizontal and vertical plane
- inclination angle of whole setup between -1.0 and +0.5 degrees

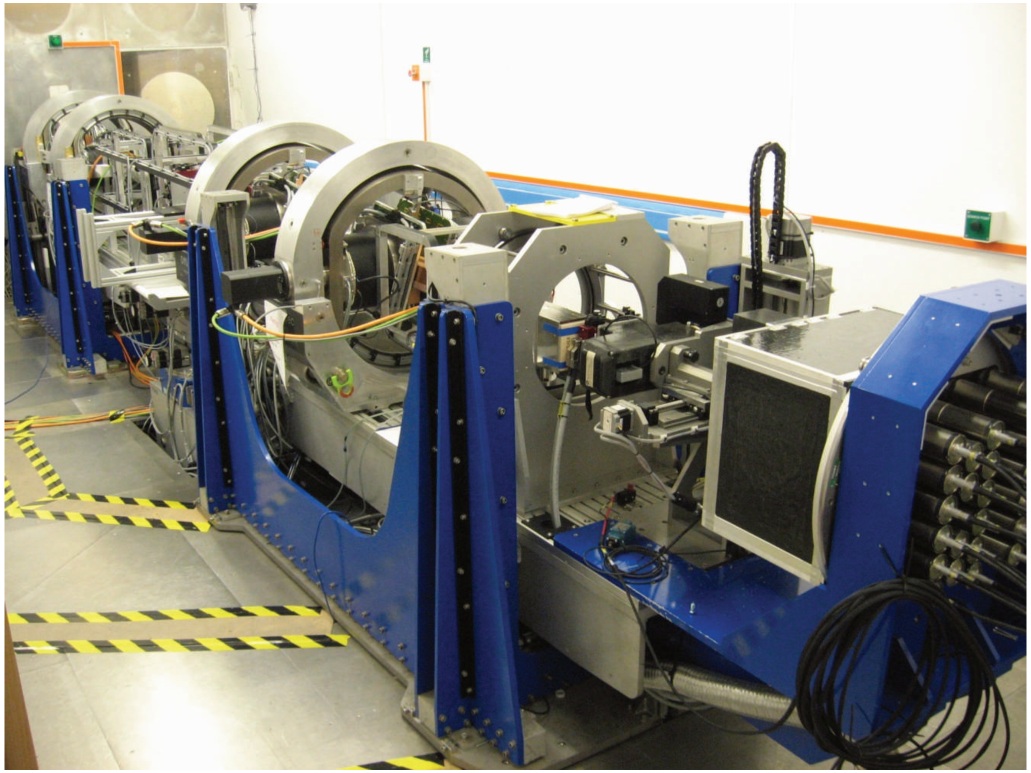
Past Measurements



OffSpec



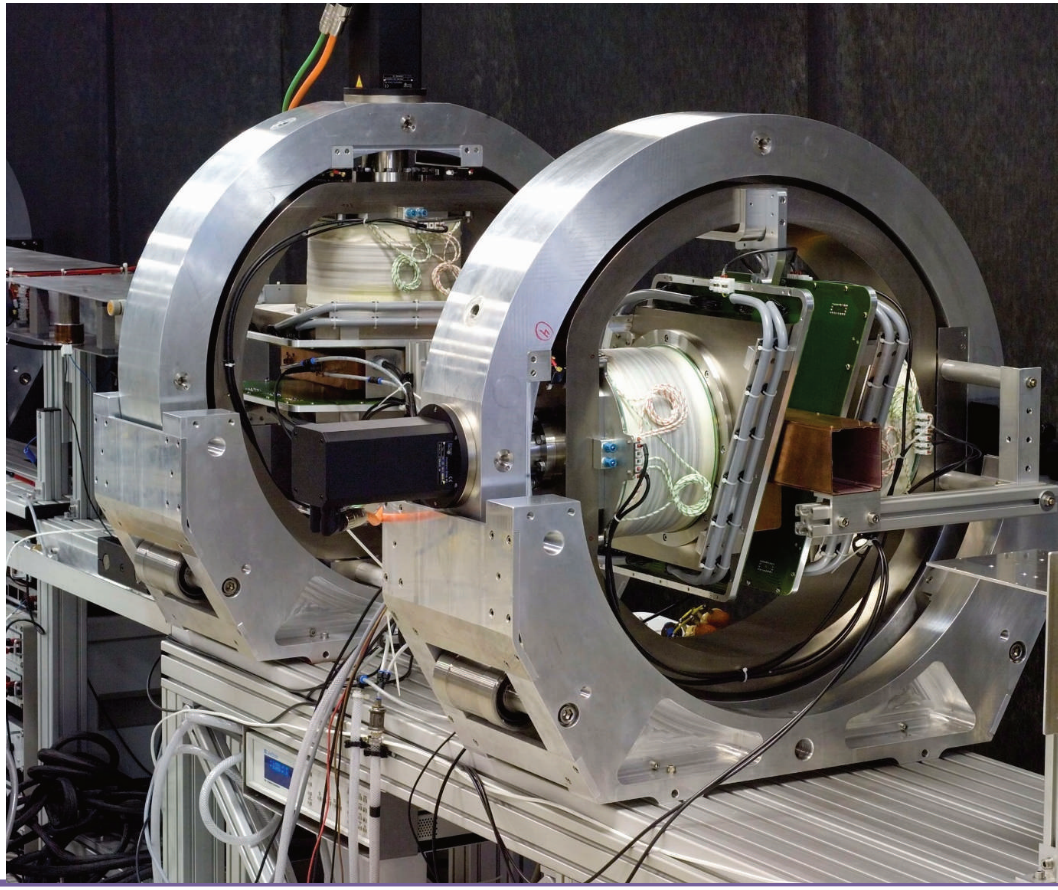
Past Measurements



OffSpec @ ISIS

Reflectometer with spin-echo option meant for SERGIS and SESANS.

Past Measurements

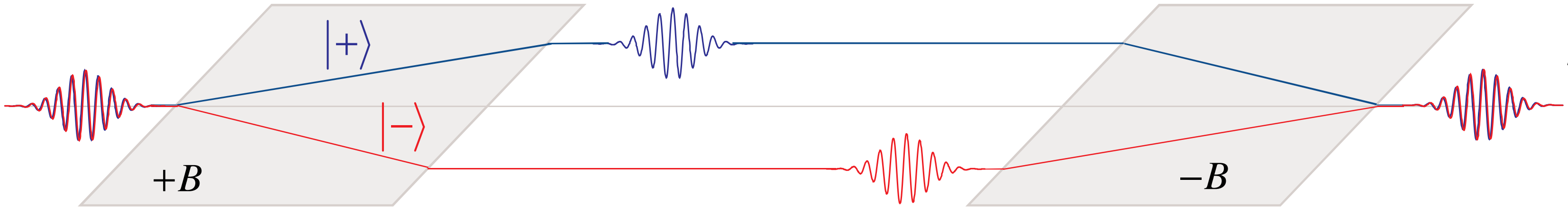


Past Measurements

$$\phi_L = \int \left(k^+(x) - k^-(x) \right) dx \propto \Delta k_g L \Delta z$$

$$k^+ = k_0 - \Delta k_g/2 - \Delta k_Z$$

$$k^- = k_0 + \Delta k_g/2 + \Delta k_Z$$



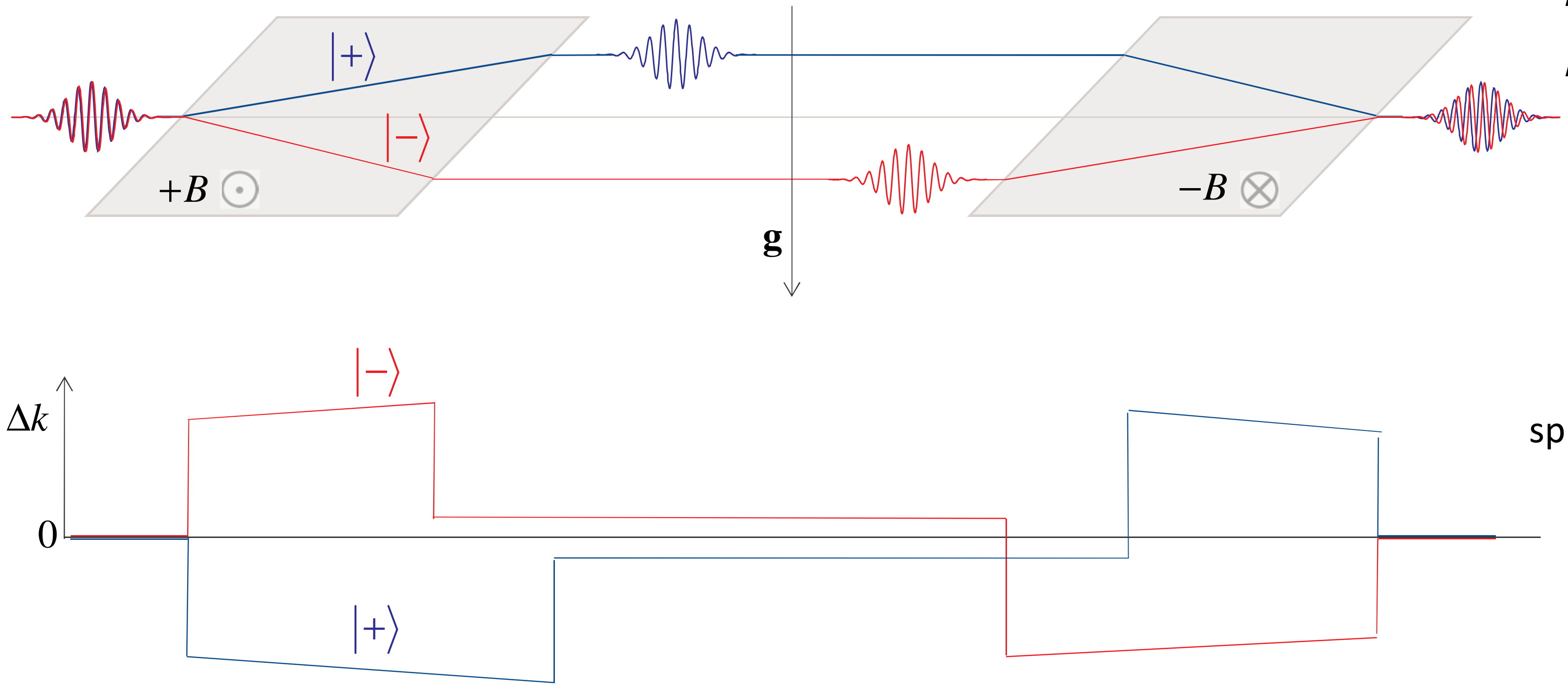
splitting in horizontal plane

Past Measurements

$$\phi_L = \int \left(k^+(x) - k^-(x)\right) dx \propto \Delta k_g L \Delta z$$

$$k^+ = k_0 - \Delta k_g/2 - \Delta k_Z$$

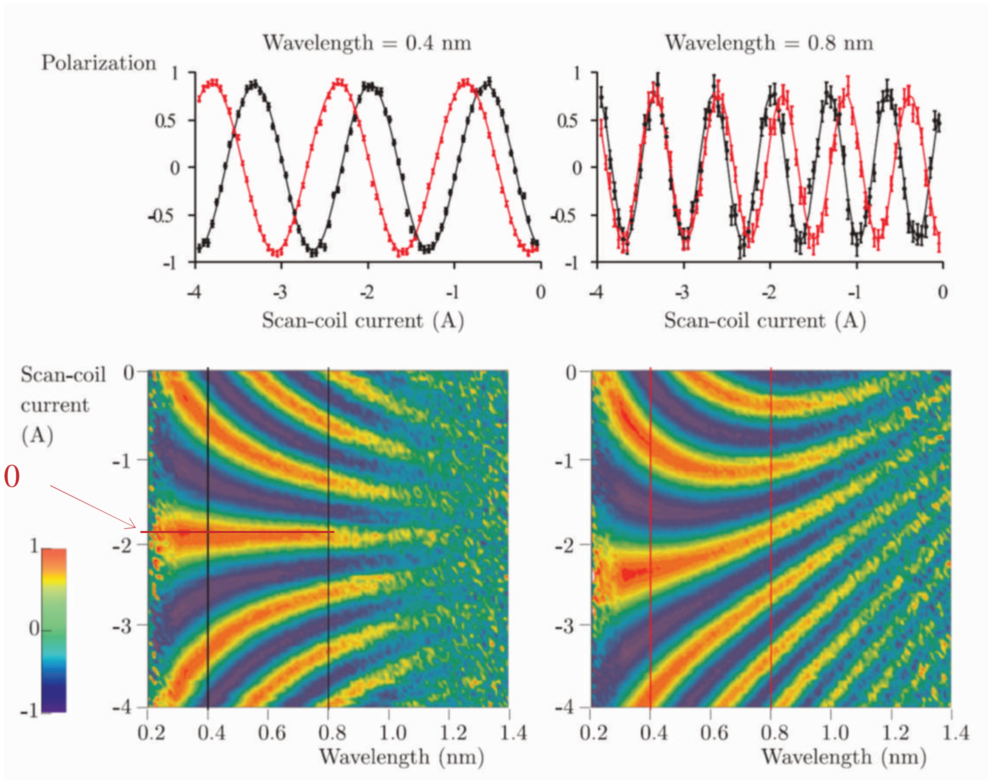
$$k^- = k_0 + \Delta k_g/2 + \Delta k_Z$$



splitting in vertical plane

Past Measurements

echo condition $\Delta B = 0$



splitting in horizontal / vertical plane

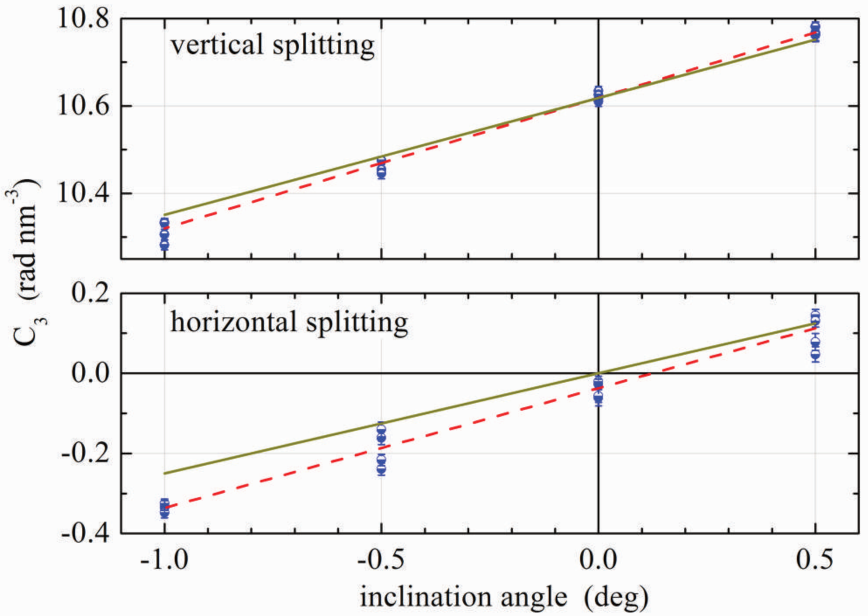
Result 1: Contour plot of the spin-echo polarisation as a function of wavelength and extra phase added to both arms

Past Measurements

Phases are described by $\Delta\phi_L = C_1\lambda + C_2\lambda^2 + C_3\lambda^3$

C_1: echo-condition
C_2: Sagnac effect
(small correction)
C_3: result of gravity

Result 2: Parameter C_3 as a function of inclination angle



theoretical value for $m_i = m_g$
best fit

Conclusion:
experimental phase shift is, within the experimental accuracy of 0.1%, in agreement with theory, when taking $m_i = m_g$

intercept C_3: exp:10.619(9) theory: 10.618(24)

some numbers

$E_0 = 0.4 - 20$ meV
$\Delta E_Z = 20$ neV
$\Delta z = 0.3 - 14$ μm
$\Delta E_g = 0.03 - 1.4$ peV

Faraday,
diary entry: March 19, 1849

What in gravity answers to the dual or antithetical nature of the forms of Force in Electricity and Magnetism?

Perhaps the *to* and *fro*, that is the ceding to the force or approach of Gravitating bodies and the effectual reversion of the force of separation of the bodies, quiescence being the neutral condition.

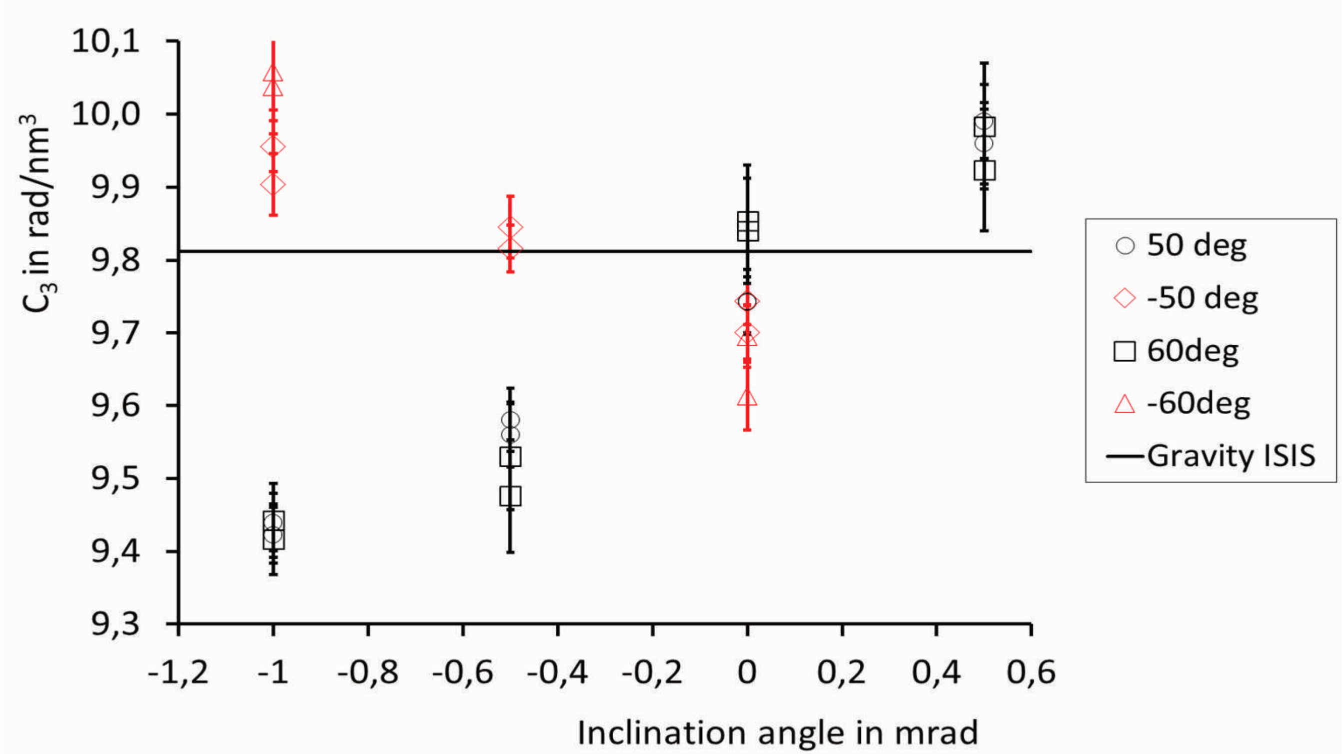
Try the question experimentally on these grounds – then the following suppositions or suggestions arise …

Bodies approaching by gravitation, and bodies separated per force, whilst gravitating towards each other, may shew in themselves or in surrounding matter or helices, *opposite currents* of electricity round line of motions as an axis. But if not moving *to* or *fro* each other, should produce no effect.

Faraday,
diary entry: March 19, 1849

All this is a dream. Still, examine it by a few experiments.

Future measurement



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BonPhysics Research and Investigations BV, Puttershoek, The Netherlands
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Future measurement

- Spin-Gravity Coupling at OffSpec – July 2019
- Follow project on research gate: https://www.researchgate.net/project/Spin-Gravity-coupling

Future measurement

$$H = \frac{k}{c}\overrightarrow{g}.\vec{S} \quad \text{or} \quad H = \frac{k}{c}\frac{\hbar}{2}\sigma \cdot \vec{g}$$

Future measurement

$$H = \frac{k}{c}\overrightarrow{g}.\vec{S} \quad \text{or} \quad H = \frac{k}{c}\frac{\hbar}{2}\sigma \cdot \vec{g}$$

$$H = -\frac{\hbar}{2}\sigma \cdot \gamma\vec{B} \qquad \overrightarrow{B_{eff}} = \vec{B} - \frac{k}{\gamma c}\vec{g}$$

Hence, the effect cannot be independently measured.

Future measurement

$$H(\vec{r}) = H_{VA}(\vec{r}) + H_{AA}(\vec{r})$$

$$H_{VA}(\vec{r}) = S_{VA}\frac{\lambda_o}{\lambda} g_V g_A\, \sigma \cdot \frac{\vec{v}}{v} \eta_{VA} \qquad S_{VA} = \frac{M}{m} H_o \frac{\lambda_o}{R} = 1.21.\, 10^{32}\ \text{eV}$$

$$H_{AA}(\vec{r}) = S_{AA}\frac{\lambda_o}{\lambda} (g_A)^2\, \sigma \cdot \left(\frac{\vec{v}}{v} \times \vec{e}_z\right) \eta_{AA} \qquad S_{AA} = \frac{M}{m} H_o \alpha \left(\frac{\lambda_o}{R}\right)^2 = 5.3.\, 10^{8}\ \text{eV}$$

yielding a possible limit on $g_V g_A$ of 10^{-48} and on $(g_A)^2$ of 5.10^{-24}

Closure

In the coherence approach picture each neutron spectrometer can be seen as a neutron interferometer.

In the coherence approach picture the polarisation of a neutron beam can be interpreted as the interference between two coupled wave functions.

Neutron spin-echo methods can be effectively used to study fundamental physics questions.

Thanks for your attention!

Dr. ir. ing. Victor de Haan

May 24-24, 2019

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