Спин-эхо малоугловое рассеяние нейтрона для исследования свойств фундаментальных взаимодействий

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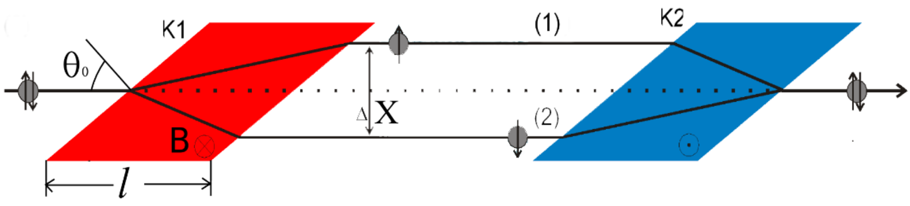
Outlook

1. SESANS method
2. Laue diffraction in perfect crystal
3. Sensitivity of SESANS+Laue diffraction
4. Possible applications
5. Demonstration experiment
6. Conclusion

SESANS method

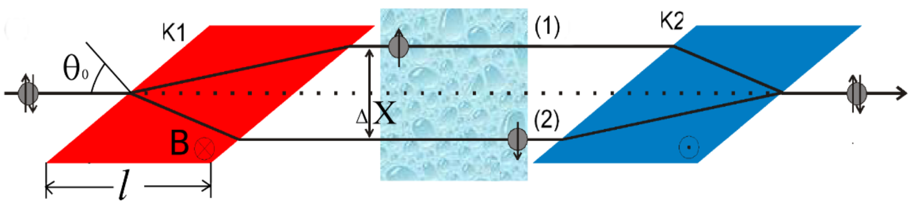


Neutron beam polarization **P** is directed perpendicularly to guiding magnetic field B. Neutron wave function can be written in form

$$\psi_{in} = \frac{1}{\sqrt{2}} \begin{pmatrix} e^{-\frac{i\varphi_0}{2}} \\ e^{+\frac{i\varphi_0}{2}} \end{pmatrix},$$

here φ_0 - neutron spin direction in azimuthally plane. Let's consider **P** parallel to X-axis ($\varphi_0 = 0$) $\Rightarrow$ $\boxed{\mathbf{P} = (1,\, 0,\, 0)}$

SESANS method - II



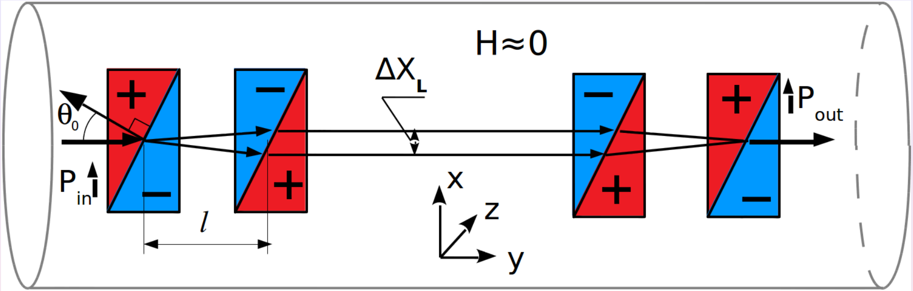
Let's apply $V_{sr}(x)$. The phase difference between these two eigenstates will be

$$\varphi_{sr} = (V_{sr}(x_0) - V_{sr}(x_0 + \Delta x))/\hbar \cdot \tau,$$

The neutron wave function on the exit of coil K2 will be

$$\psi_{out} = \frac{1}{\sqrt{2}} \begin{pmatrix} e^{-\frac{i\varphi_{sr}}{2}} \\ e^{+\frac{i\varphi_{sr}}{2}} \end{pmatrix} \Rightarrow \boxed{\mathbf{P} = (\cos\varphi_{sr}, \sin\varphi_{sr}, 0)}$$

Alternative SESANS layout

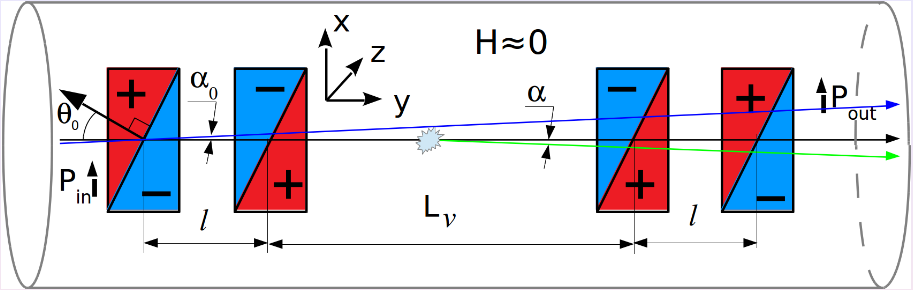


The value of spatial splitting

will be two times more than for the previous scheme

$$\Delta X_L = \frac{2\mu B}{E} \cdot l \cdot \tan\theta_0$$

Classical SESANS interpretation



Single coil make a spin modulation in X direction $\underline{\phi(\mathrm{x}) = 2B\gamma_n \tan(\theta_0)\frac{\mathrm{x}}{v}}$

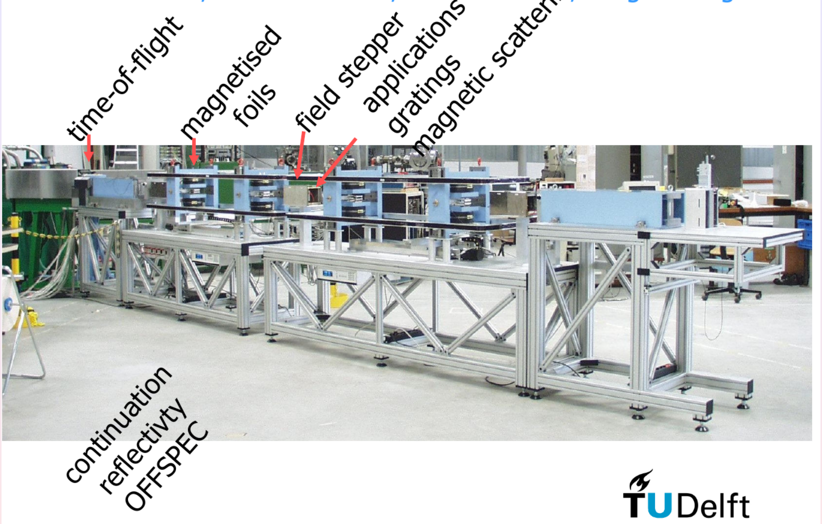
Angle of neutron spin rotation will be

$$\phi = \frac{2B\gamma_n \tan(\theta_0)}{v}(0 - l\alpha_0 - (L_v + l)\alpha_0 + (L_v + 2l)\alpha_0) \equiv 0$$

After the scattering on α angle $\boxed{\phi(\alpha) = \frac{2B\gamma_n \tan(\theta_0)}{v} \cdot l\alpha}$

Delft University of Technology: SESANS

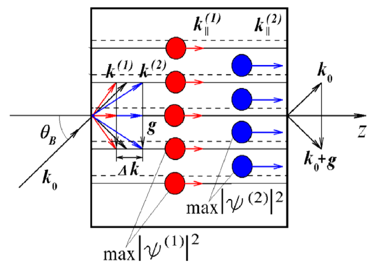
Wim Bouwman, Theo Rekveldt, Wicher Kraan, Serguei Grigoriev



$$\boxed{\Delta x \simeq (0.020 - 20)\mu m}$$

Two wave approximation [1]

For the case of neutron diffraction on single srystallographic plane, wave function is a superposition of direct and reflected wave



$$\psi^{(1)} = \frac{1}{\sqrt{2}}[e^{i\boldsymbol{k}^{(1)}\boldsymbol{r}} + e^{i(\boldsymbol{k}^{(1)}+\boldsymbol{g})\boldsymbol{r}}] = \sqrt{2}\cos(\boldsymbol{g}\boldsymbol{r}/2)\exp[(\boldsymbol{k}^{(1)}+\boldsymbol{g}/2)\boldsymbol{r}]$$

$$\psi^{(2)} = \frac{1}{\sqrt{2}}[e^{i\boldsymbol{k}^{(2)}\boldsymbol{r}} - e^{i(\boldsymbol{k}^{(2)}+\boldsymbol{g})\boldsymbol{r}}] = i\sqrt{2}\sin(\boldsymbol{g}\boldsymbol{r}/2)\exp[i(\boldsymbol{k}^{(2)}+\boldsymbol{g}/2)\boldsymbol{r}]$$

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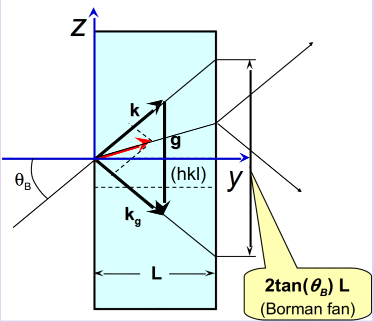
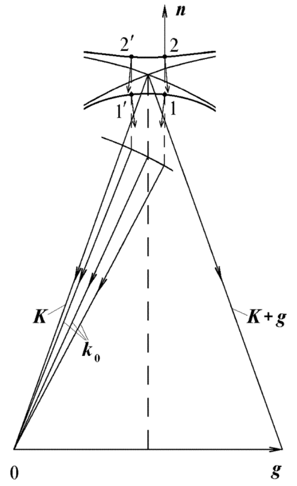
[1] Voronin V., Report on FKS School 2012, http://lns.pnpi.spb.ru/media/fks2012/Voronin.pdf

Dispersion surface

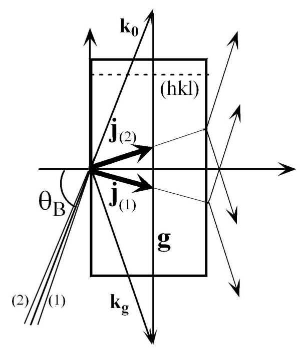
Direction of neutron current is normal to dispersion surface

$$\boldsymbol{j} = \frac{\hbar}{m}\left(|a_g|^2 \boldsymbol{k_g} + |a_0|^2 \boldsymbol{k}\right)$$





Neutron trajectories in crystal



Symmetrical Laue diffraction.

$\mathbf{j}_{(1)}$ and $\mathbf{j}_{(2)}$ are the neutron fluxes for two direction of incident beam.

Effect of diffraction enhancement

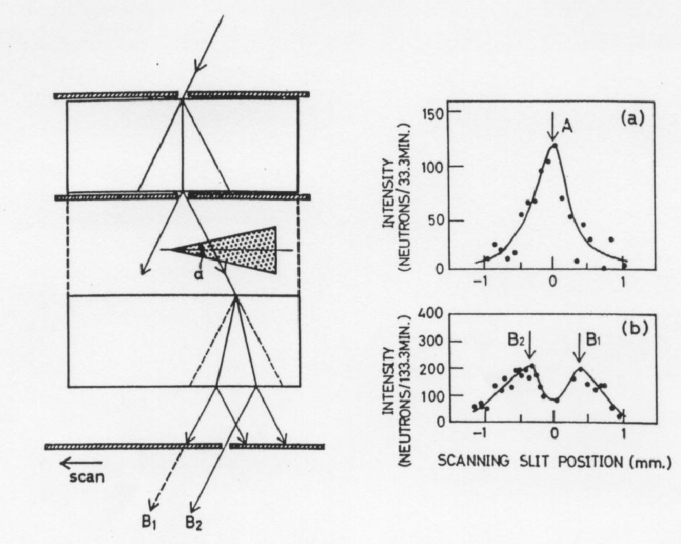
The neutron in the crystal changes the momentum direction by the angle of Ω (by several tens degrees) while the incident neutron beam deflects by the Bragg width (within a few arc seconds)

$$\Omega = \Delta\theta \cdot \frac{E}{2v_g} \Rightarrow \Delta\theta \cdot 10^5$$

The same phenomenon occurs then not direction but neutron energy is changed according to the

$$\Delta\theta = \frac{\Delta E}{2E} \tan\theta_B$$

Measurement the neutron prism refraction[2]



$\Leftarrow$ no refracting prism

$\Leftarrow$ 0.032 arc sec $=$ $= 1.5 \cdot 10^{-7}$ rad refracting prism

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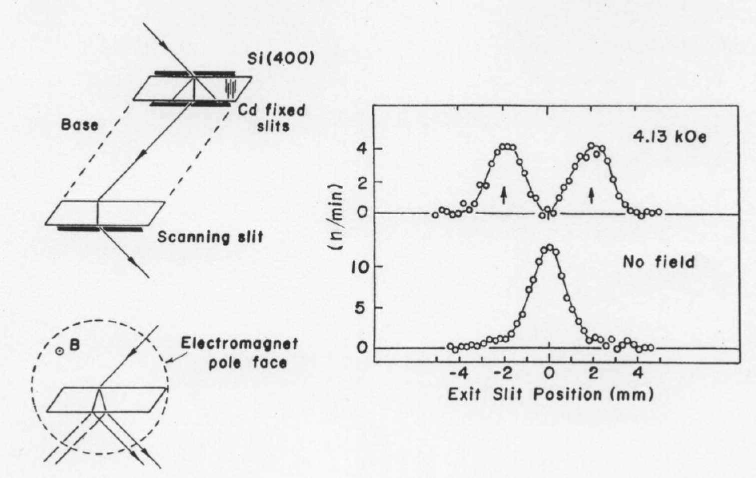
[2] S.Kikuta et al., J. Phys. Soc. Japan, **39** (1975) 471

Change neuron length wave in magnetic field[3]



⇐ 4.13 kOe magnetic field $\Delta E = 50$ neV

⇐ no magnetic field

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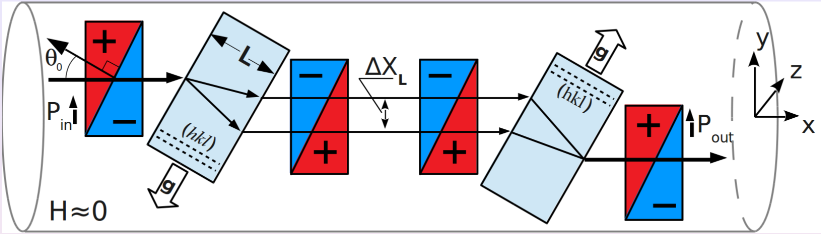
[3] A.Zeilinger, C.G.Shull, Phys.Rev.B **19** (1979) 3957

SESANS + Laue diffraction



The values of neutron splitting

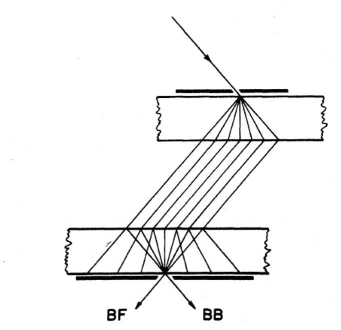
Laue diffr.+SESANS Standard SESANS

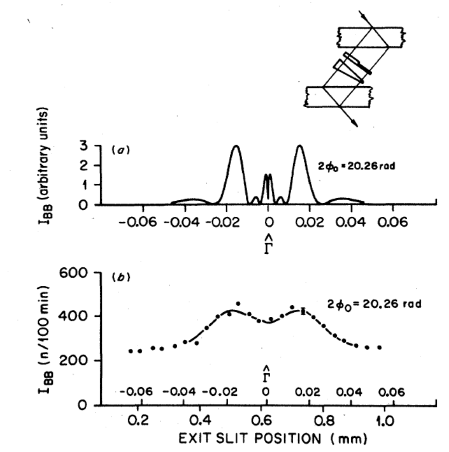
$$\Delta X_L = \frac{2\mu B}{v_g} L \sin\theta_B \cdot \tan\theta_0 \iff \Delta X = \frac{2\mu B}{E} \cdot l \cdot \tan\theta_0$$

About $K_g = \frac{E}{v_g} \Rightarrow 10^5$ times more.

ΔX_L for silicon (220) and (100) quartz planes, $L = 10$ cm, $\tan\theta_0 = 1$ and $\theta_B = 65^0$ can be $\boxed{\sim 40\mu\text{m and} \sim 120\mu\text{m}}$ for the $\boxed{B = 1\ \text{G}}$.

Two crystal focusing[4]





Spatial resolution

$$\boxed{x_w = \frac{\Lambda \tan(\theta_B)}{2\pi} \sim (10-50)\mu m}$$

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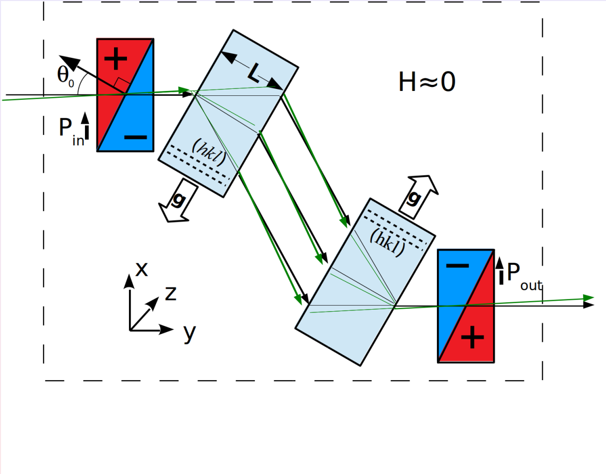
[4] x-rays - Инденбом ВЛ., Слободецкий И.Ш., Труни К.Г. ЖЭТФ (1974) 66 1110
neutron - J. Arthur, C. G. Shull, A. Zeilinger, Phys. Rev. B,32 5753 (1985)

New layout of SESANS + Laue diffraction



Advantages -

- More luminosity
- Only two coils
- More space in working area.

Disadvantage -

- Nobody saw the two crystal diffraction focusing effect in separated crystals

Sensitivity of SESANS + Laue

Angle of spin rotation

$$\varphi_v = \frac{dV}{dx}\Delta X_L \cdot \frac{L_v}{\hbar v_n} \simeq 5 \cdot 10^{12} \cdot \frac{dV}{dx}[eV/cm]$$

For the (100) quartz plane (d=4.255Å, $v_g = 1.8 \cdot 10^{-8}$eV),
$\theta_B = 65^0$,$L = 10$cm, $\tan\theta_0 = 3$, $B = 100$G, $L_v = 100$cm
Spatial period $\Rightarrow 0.25$ mm

Statistical sensitivity

Accuracy of spin rotation measurement can be about 10^{-4} rad, so

$$\sigma\left(\frac{dV}{dx}\right) \simeq 2 \cdot 10^{-17}[eV/cm] \simeq 2 \cdot 10^{-8} m_n g$$

$$\boxed{\sigma(\alpha) \simeq 10^{-12} rad}$$

Motivations

- Test of a neutron electro-neutrality $\frac{dV}{dx} = E_e q_n$.

$$\sigma(\varphi) = 10^{-4} \Longrightarrow \underline{\sigma(q_n) \simeq 2 \cdot 10^{-22} e}$$

about one orders better present accuracy*.

*J.Baumann, R.Gahler, J.Kalus, W.Mampe, PR D37, 3107 (1988)

- Study the neutron gravity in the Earth with the sensitivity

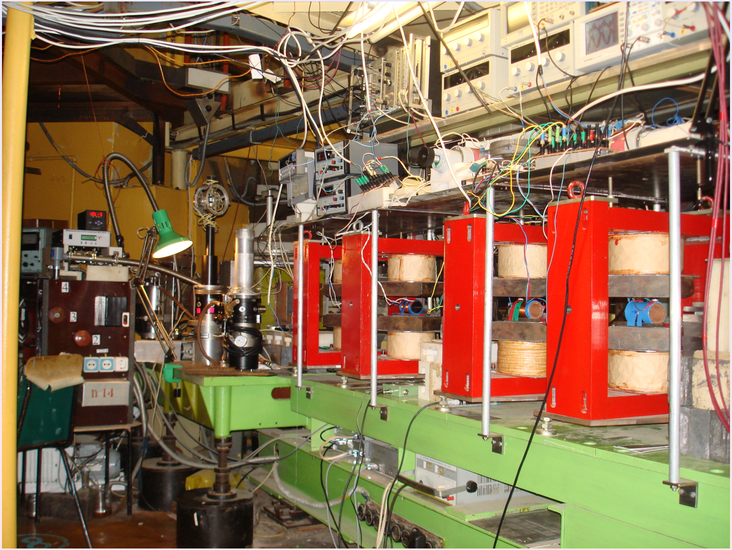
$$\underline{\sigma(m_n g) \sim 10^{-8} m_n g}$$

- Search for the new fundamental interaction of a neutron with the matter (5-th force) at the range distance about $0.01 - 1$ cm
- Measurement of a matter refracting index $\Longrightarrow$ amplitude of neutron scattering with stat. accuracy

$$\underline{\sigma(a_n) \sim (10^{-5} - 10^{-6})} \; for\ condenced\ matter$$

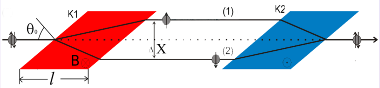
$$\underline{\sigma(a_n) \sim (10^{-3} - 10^{-4})} \; for\ gas$$

WWR-M SESANS



Measurement a neutron refraction by SESANS[5]

SESANS at WWR-M reactor (PNPI, Gatchina)



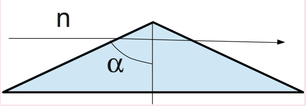
Neutron length wave - 2.3 Å,

$B = (40 \div 800)\mathrm{Oe}$

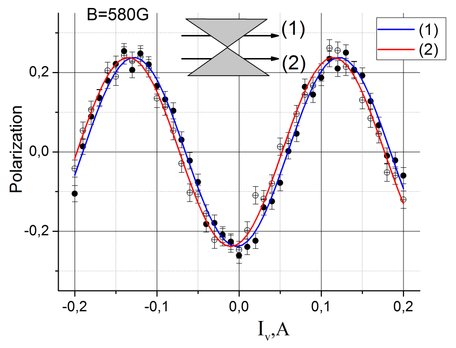
$\theta_0 = 45^0$

$l = 50\mathrm{cm}$

Δx reached about 200 nm.



Example of experimental curves



We use the quartz crystal prism with the vertex angle about 156^0 for neutron beam refraction.

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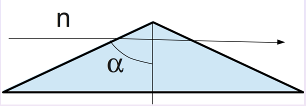
[5] Thanks to Axelrod L.A. and Zabenkin V.N.

Neutron refraction in quartz prism



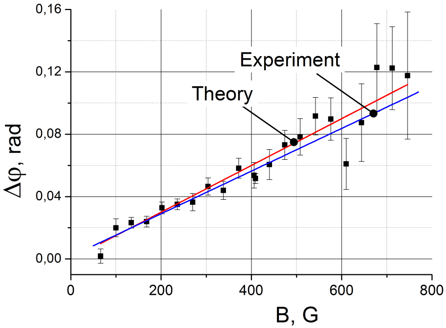
Value of phase shift due to refraction in prism

$$\Delta\varphi_r = \frac{V_0}{E}\frac{2\pi}{\lambda}\Delta x \tan\alpha$$

The used quartz prism

$V_0 \simeq 10^{-7}$ eV, $\alpha = 78^0$

The phase shift dependence on a value of magnetic field in main coils.



Summary

New approach for precise neutron spectrometry is proposed.

It is based on two principle

- spin interferometer technique SESANS
- effects in perfect crystal Laue diffraction

A method sensitivity can reach

$$\sigma\left(\frac{dV}{dx}\right) \simeq 10^{-16}[eV/cm] \Rightarrow \underline{\sigma\left(E_n\right) \sim 10^{-14}\ eV}$$

This approach can be applied for

- Test of a neutron electro-neutrality with the best accuracy
- Study the neutron gravity in the Earth with the sensitivity
- Search for the new fundamental interaction
- Precise measurement of an amplitude of neutron scattering