# Interaction of neutron with accelerating matter

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# Contents

# Interaction of neutron with moving grating (1981-89)

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2. Klein A.G., Werner S.A.Rep.Prog.Phys., 46 (1983) 259.
3. Horn V.A., Zeilinger A., Klein A.G., Opat G.I. Phys. Rev. A. 28. (1983) 1.
4. Arif M., Kaiser H., Werner S.A., Cimmino A.,et al. Phys. Rev. A. 31 (1985) 1203.
5. Bonse U., Rumpf A. Phys. Rev.A. 37 (1988) 1059.
6. Arif M., Kaiser H., Clothier R., Werner S.A., et al. B. 151 (1988) 63.
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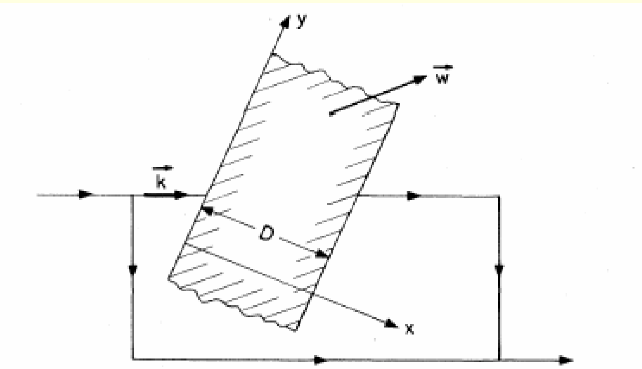



FIG. 1. Phase plate of thickness $D$ moving with velocity $\vec{w}$ in one beam path of an interferometer. $x$-$y$ coordinate system is at rest but $x=0$ coincides with the plate entrance surface at $t=0$ as shown.

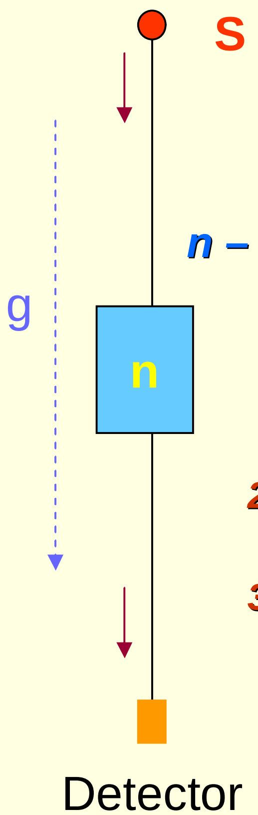
***Only the case of v=const was considered***

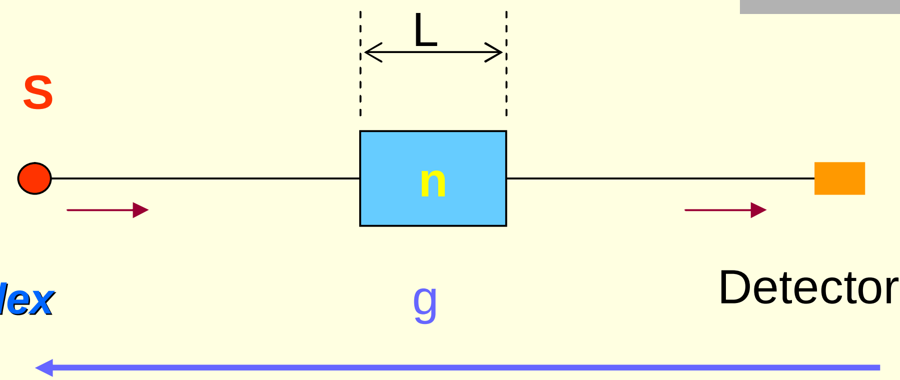
***The only observable effect is the phase shift***

***The case of accelerating matter***

1. *F. Kowalski Phys. Lett.A. 182 (1993), 335*
2. *V.G.Nosov, A.I.Frank Yad. Phys, 61 (1998), 686*

# Accelerating matter and the equivalence principle




***n – refraction index***

1. ***In both cases the energy, measured by the detector, is the same due to the equivalence principle***
2. ***Introduction of the refracting slab does not change the energy due to the energy conservation law***
3. ***Delay time due to refraction is Dt***

$$\Delta\tau = \frac{L}{v}\left(\frac{1-n}{n}\right)$$

***During this time detector will accelerated***

$$\Delta v = g\Delta\tau$$

$$\Delta E = mg\frac{1-n}{n}L$$

***F.V.Kowalski, 1993***

# Elementary theory (1)


## Main assumptions

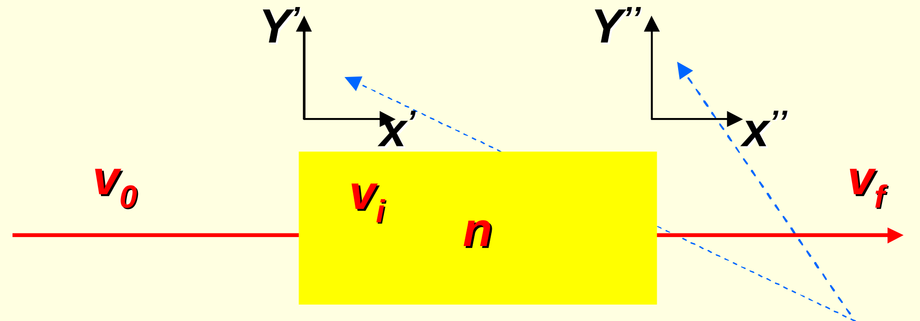
***1. Effective optical potential is also valid in the case of accelerated matter***

$$\mathbf{k}_i^2 = \mathbf{k}^2 - 4p r \mathbf{b} \qquad \mathbf{U} = \frac{2p\mathbf{h}^2}{\mathbf{m}} r\mathbf{b} \qquad \mathbf{v}_i^2 = \mathbf{v}^2 - \mathbf{v}_b^2 \qquad \mathbf{v}_b^2 = \frac{\mathbf{2}}{\mathbf{m}}\mathbf{U}$$

***2. Quasi – classical approach is correct***

$$e(\mathbf{t}) >> \frac{\mathbf{h}}{t}$$

# Elementary theory (2)




$$v_i = v_i' + V_1 \qquad v_i' = \sqrt{v_0'^2 - v_b^2} \qquad t = t_1$$

$$v_i'' = v_i - V_2, \qquad v_f''^2 = v_i''^2 + v_b^2 \qquad t = t_2$$

$$v_f = V_2 + \sqrt{v_0^2 - 2V_1 v_0 + V_2^2 - 2(V_2 - V_1)\left[V_1 + \sqrt{(v_0 - V_1)^2 - v_b^2}\right]}$$

# Elementary theory (3)

$$\mathbf{v_f} - \mathbf{v}_0 \cong \frac{\mathbf{v}_0 - \sqrt{\mathbf{v}_0^2 - \mathbf{v_b}^2}}{\mathbf{v}_0}\left(\mathbf{V}_2 - \mathbf{V}_1\right) \longrightarrow e_\mathbf{f} - e_0 \cong \mathbf{m}\mathbf{v}_0\left(\mathbf{v_f} - \mathbf{v}_0\right)$$

$$\mathbf{V}_1, \mathbf{V}_2 << \sqrt{\mathbf{v}_0^2 - \mathbf{v_b}^2}, \; \mathbf{v}_0$$

$$\frac{\mathbf{L}}{\sqrt{\mathbf{v_o^2} - \mathbf{v_b^2}}} << t$$

$$\mathbf{V_2 - V_1} \longrightarrow \mathbf{w(t)} = \frac{\mathbf{dV}}{\mathbf{dt}}$$

$$\mathbf{v_f - v_0} \cong \frac{\mathbf{v_0 - \sqrt{v_0^2 - v_b^2}}}{\mathbf{v_0\sqrt{v_0^2 - v_b^2}}}\mathbf{Lw(t)}$$

$$\Delta E = e_\mathbf{f} - e_\mathbf{0} \cong \frac{\mathbf{v_0 - \sqrt{v_0^2 - v_b^2}}}{\mathbf{\sqrt{v_0^2 - v_b^2}}}\mathbf{mw(t)L}$$

$$\Delta \mathbf{E} = \mathbf{mw}\frac{\mathbf{1 - n}}{\mathbf{n}}\mathbf{L}$$

$$k_0 L >> \frac{\varepsilon_0}{U}$$

***V.G.Nosov, A.I.Frank, 1997***

# Oscillating slab

***Most realistic case from point of view of experiment***

$$\xi(t) = a\sin\Omega t$$

$$V = \frac{d\xi}{dt} \approx a\Omega << \sqrt{v_0^2 - v_b^2},\ v_0$$

$$\varepsilon_f - \varepsilon_0 = ma\Omega\left(v_0 - \sqrt{v_0^2 - v_b^2}\right)\left[\cos\Omega t - \cos\Omega\left(t - \frac{L}{\sqrt{v_0^2 - v_b^2}}\right)\right]$$

$$\varepsilon_f - \varepsilon_0 \cong -ma\Omega^2 L\,\frac{v_0 - \sqrt{v_0^2 - v_b^2}}{\sqrt{v_0^2 - v_b^2}}\sin\Omega t \qquad \frac{\Omega L}{\sqrt{v_0^2 - v_b^2}} << 1.$$

$$\Delta E \cong -ma\Omega^2 L\,\frac{1 - n}{n}\sin\Omega t$$

$$k_0 L >> \frac{v_0}{V}\frac{\varepsilon_0}{U}$$

# Preliminary estimations of the experimental conditions

$$\Delta E \cong -\mathbf{ma}\Omega^2\mathbf{L}\frac{\mathbf{1-\nu}}{\mathbf{\nu}}\mathbf{\sin}\,\Omega\mathbf{t} \qquad \mathbf{k_0L} >> \frac{\mathbf{v_0}}{\mathbf{V}}\frac{\varepsilon_0}{\mathbf{U}}$$

***Si slab 0.6 mm thick***

$\Omega = \mathbf{2}\pi\mathbf{f} \approx \mathbf{250rad/sec}$ $\quad \mathbf{w} \approx \mathbf{a}\Omega^2$ $\approx 7.5\times 10^3 \approx 7.5g$

$v_0 \approx 450$ *cm/sec* $\quad k_0 \approx 7\times 10^5 cm^{-1}$ $\quad V \approx 30$ *cm/sec*

$$\frac{\mathbf{1-\nu}}{\mathbf{\nu}} \approx \mathbf{0.45}$$

$$k_0L \approx 4.2\times 10^4 >> \frac{\mathbf{v_0}}{\mathbf{V}}\frac{\varepsilon_0}{\mathbf{U}} \approx 10$$

$$\Delta E_{max} \approx 2\times 10^{-10}\,eV$$

# How to measure that?


толщину образца) выполняется не хуже. В итоге

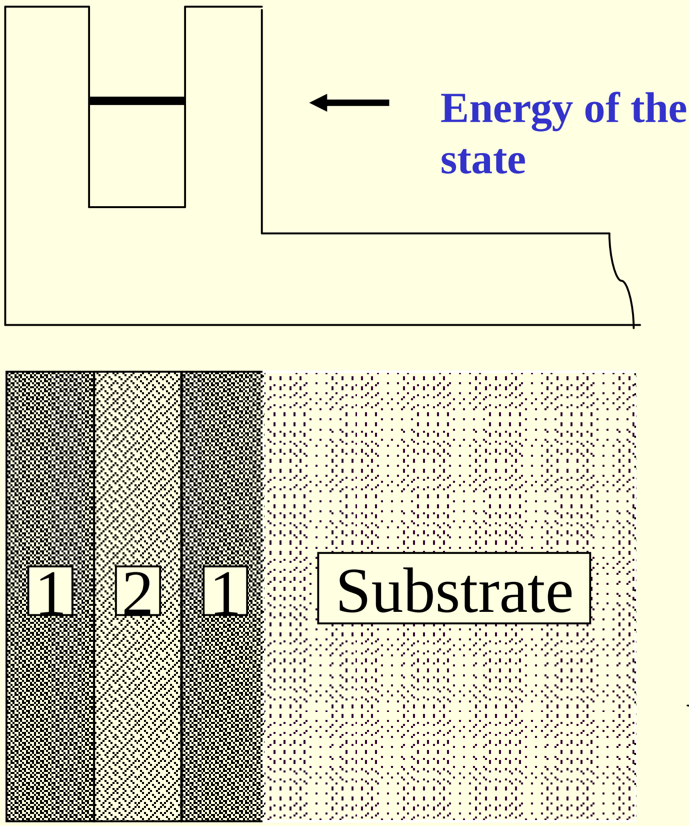
$$\varepsilon_f - \varepsilon_0 \approx -\beta \sin \Omega t , \qquad (7.1)$$

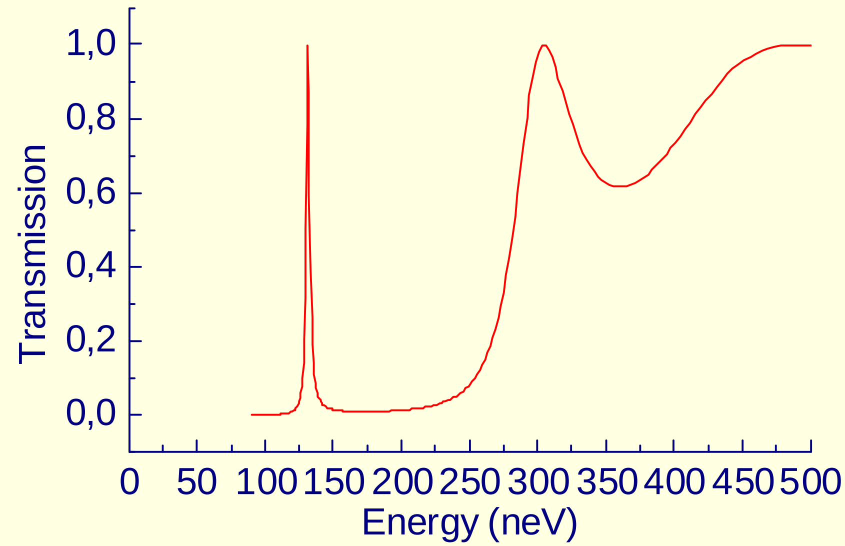
причем характерное изменение энергии нейтрона составляет в данном случае $\beta \cong 0.6$ **нэВ**. Эта величина не слишком далека от типичных значений энергетического разрешения спектрометров УХН. Отметим еще,

что в данном случае колебательного движения речь идет об измерении временной зависимости энергии нейтрона. Одна из возможностей состоит в использовании гравитационного спектрометра с интерференционными фильтрами [**21-22**]. По оценкам, чувствительность этого прибора к сдвигу энергии может быть порядка $\mathbf{10^{-11}}$ **нэВ**. Необходимо только, чтобы разброс времен пролета нейтронов между образцом и детектором был заметно меньше периода колебаний образца.

***It was proposed in 1997 to use Neutron Interference Filters for the detection of this effect***

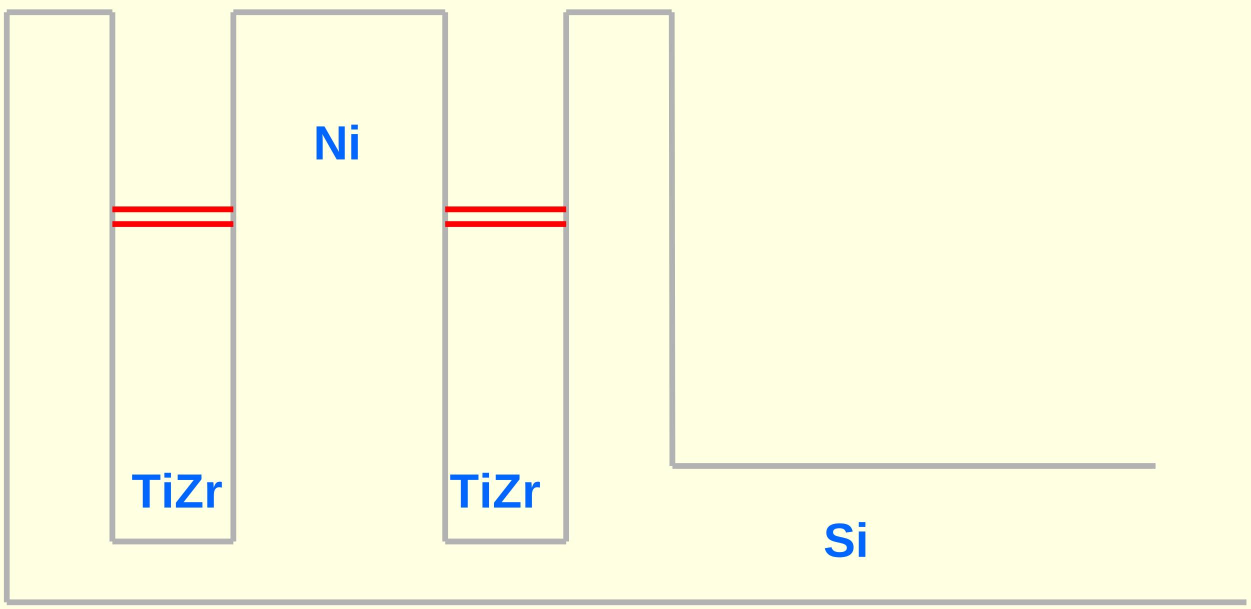
# Neutron Interference Filter as a quantum monochromator




$$U_{1,2} = \frac{2\pi\hbar^2}{m}(\rho b)_{1,2}$$

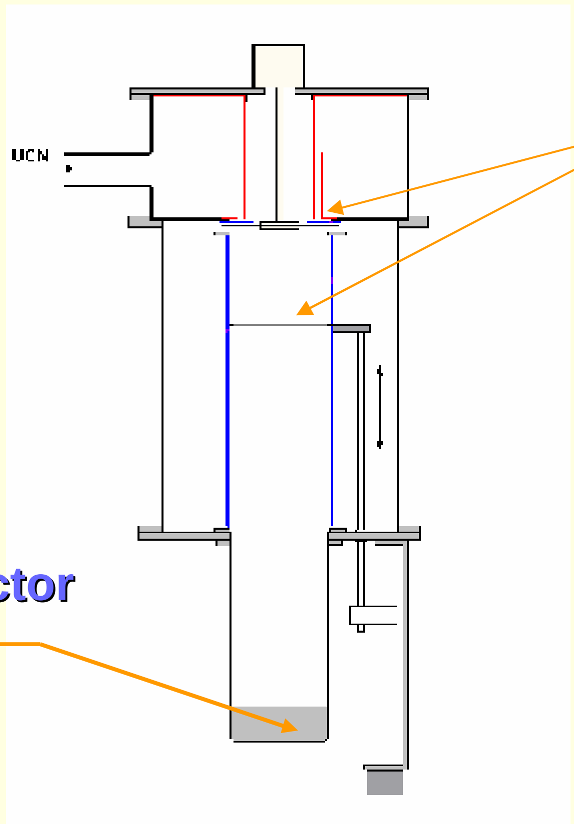
# Potential structure of the filter - monochromator



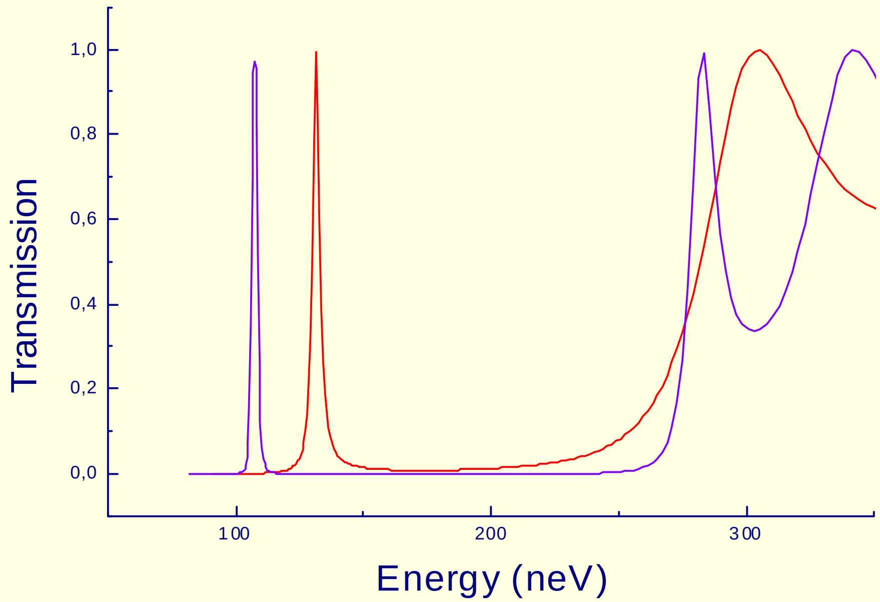
# UCN spectrometer and Interference filters

**Two NIFs with variable distance between them**

**mg=1.02 neV**

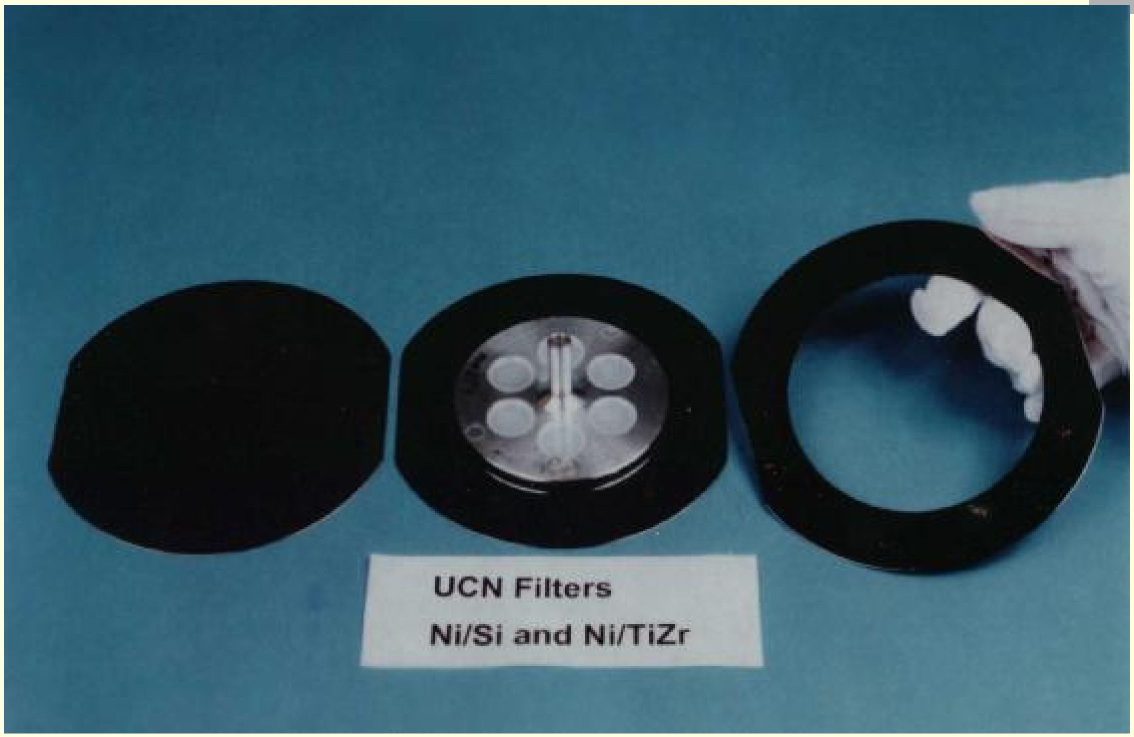



**Detector**



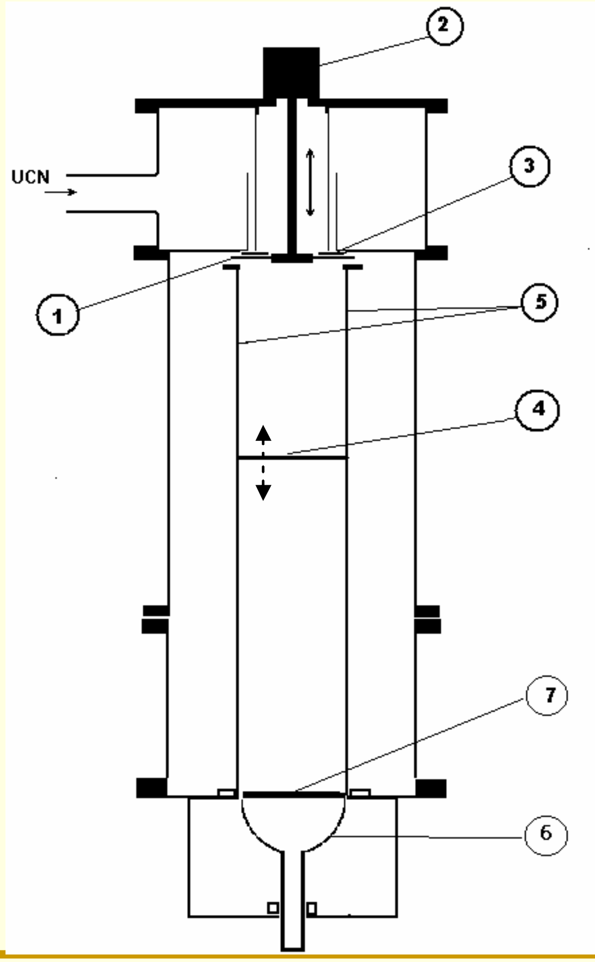

1997

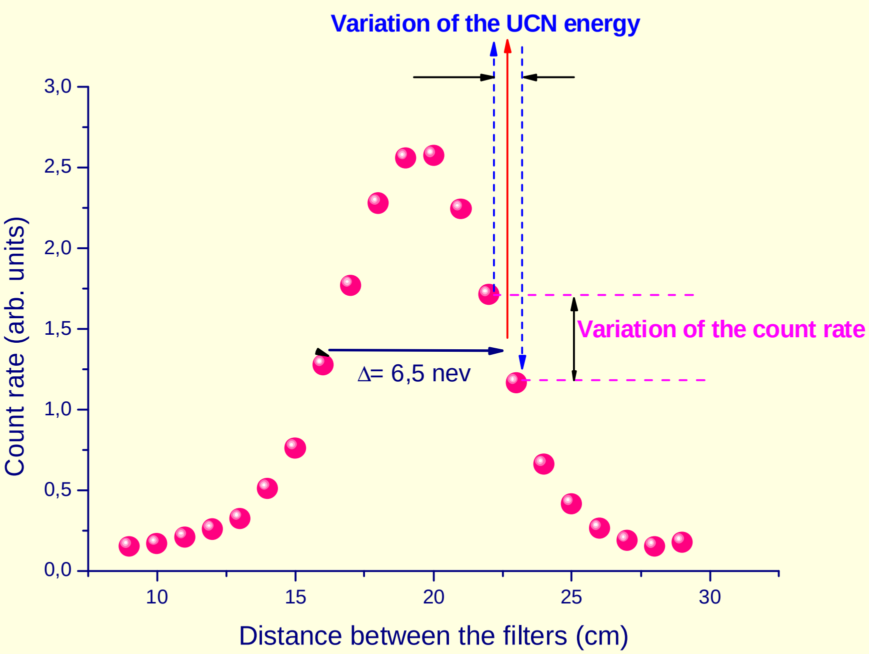
# Interference filters – neutron Fabry –Perot interferometers




**Multilayer structures on a Si wafer.**
**Number of layers 5-120. Typical thickness of a layer 200-300 Å. Uniformity 2-3%**

# Idea of the experiment




**DE ≈ 2´10$^{-10}$ eV**

# Methodical Problem 1: filters vibration

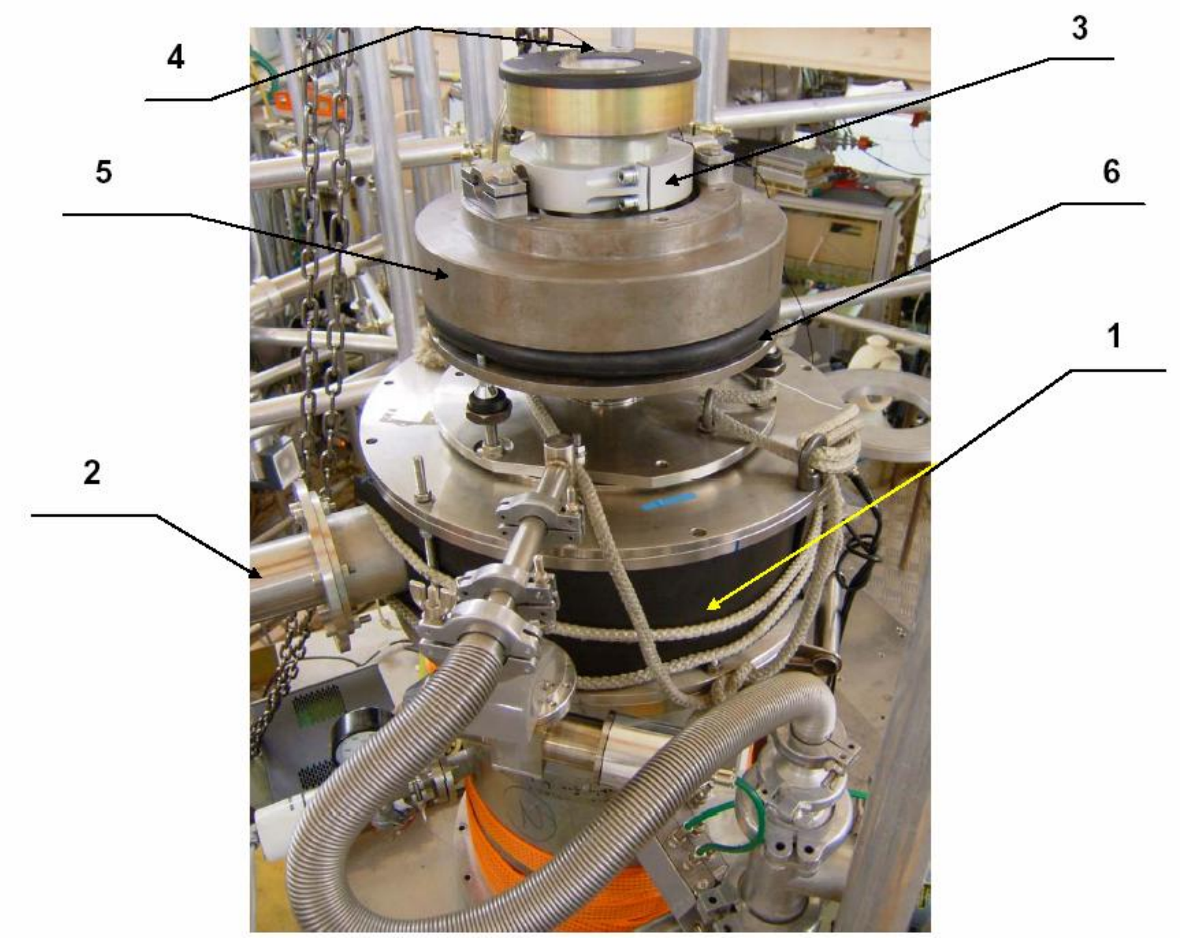
***Velocity of the vibrating filter*** $\quad \mathbf{v}_{\mathbf{vibr}} \gg \mathrm{x}\mathrm{W}$

$$\frac{\mathrm{D}\mathbf{E}}{\mathbf{E}} \gg \frac{\mathbf{2v}_{\mathbf{vibr}}}{\mathbf{v}_{\mathbf{0}}} \qquad \mathrm{D}\mathbf{E} = \mathrm{x}\mathbf{2E}\frac{\mathrm{W}}{\mathbf{v}_{\mathbf{0}}}$$

$E \approx 10^{-7}$ $\quad W \approx 250$ $\quad v_0 \approx 450$

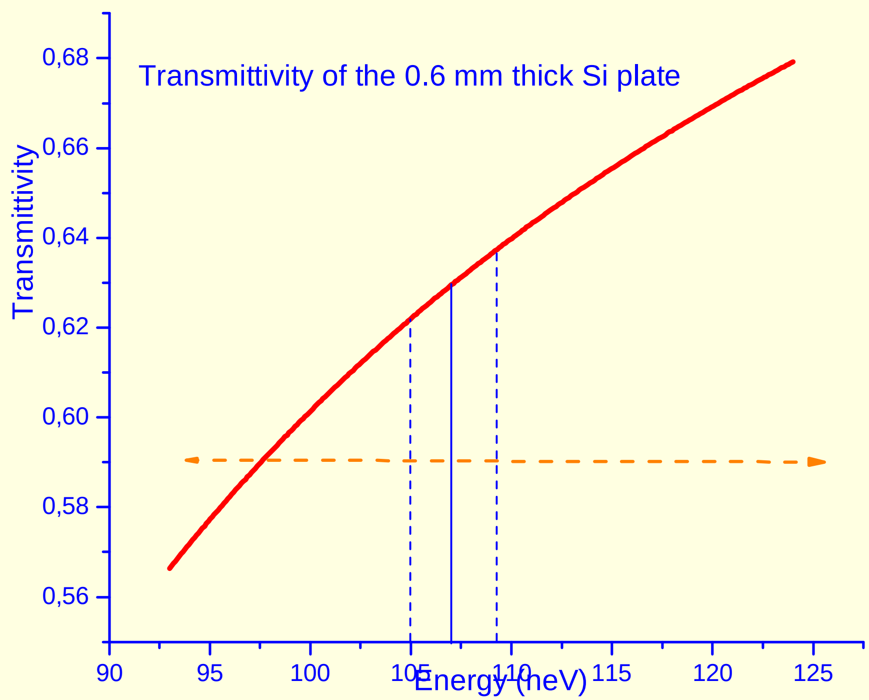
***Vibration with amplitude $\xi \approx 10$ mkm is equivalent to the energy oscillation with amplitude DE ≈ $10^{-10}$ eV***

# Experimental installation



# Methodical Problem 2

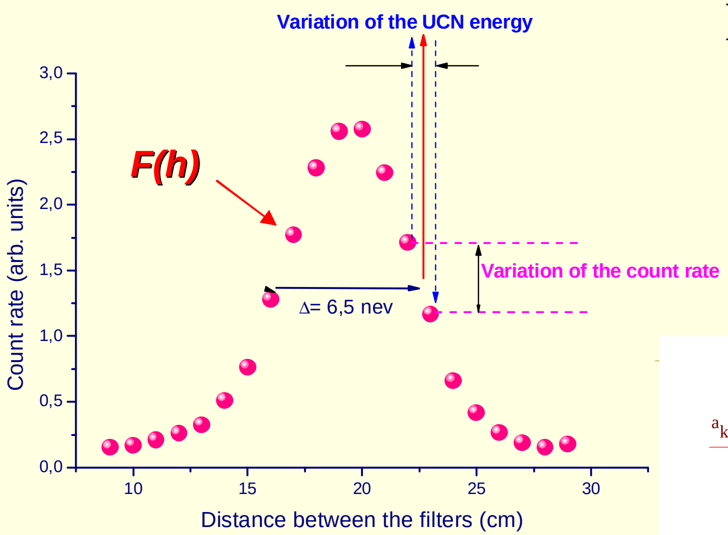
***Variation of the slab velocity results in the variation of transmittivity***




$$\mathbf{w} = -\mathbf{a}\Omega^2 \mathbf{Sin}(\Omega \mathbf{t})$$

$$\mathbf{V} = \mathbf{a}\Omega \, \mathbf{cos}(\Omega \mathbf{t})$$

# Experimental strategy



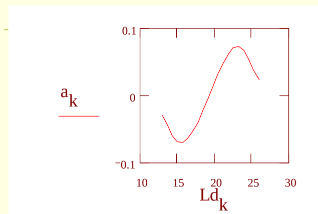

$$I \approx I_0\left[1+\alpha\sin(\Omega t)-\beta\cos(\Omega t)\right] \quad a,b \ll 1$$

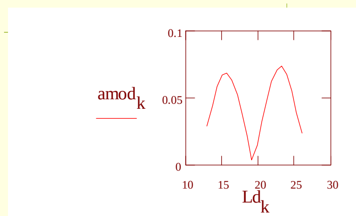
$$\alpha \propto \frac{dF}{dh}$$

$$\beta \propto \frac{F(h)-Bg}{F(h)}$$

***Effect of acceleration***

***Velocity effect***



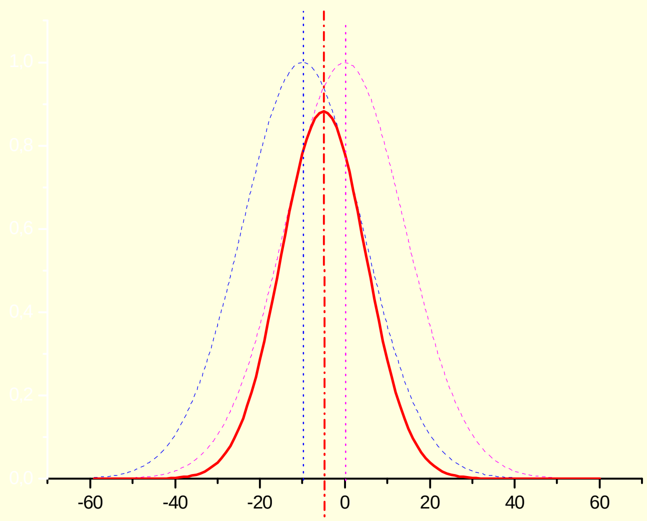



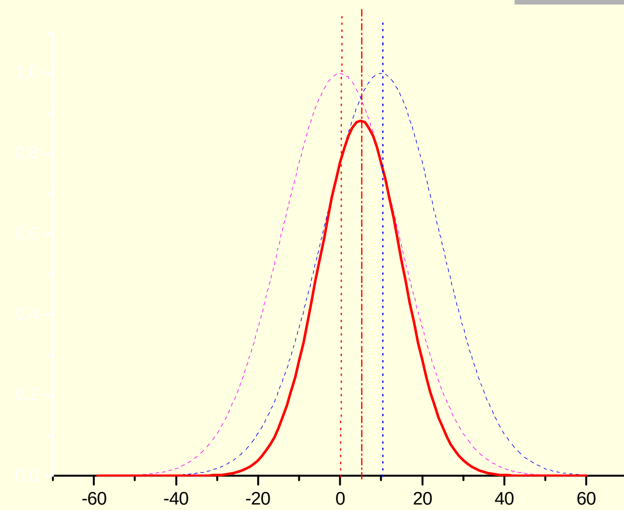

$$P(t)=\frac{I(t)}{I_0}=1+\sqrt{\alpha^2+\beta^2}\cdot\cos(\Omega t+\varphi)$$

$$\varphi=\arcsin\frac{\alpha}{\sqrt{\alpha^2+\beta^2}}$$

***Experimental strategy – the measurement of the phase (and amplitude) as a function of the distance between filters***

# Methodical Problem 3. Dependence of the transmitted spectrum on the position of analyzer



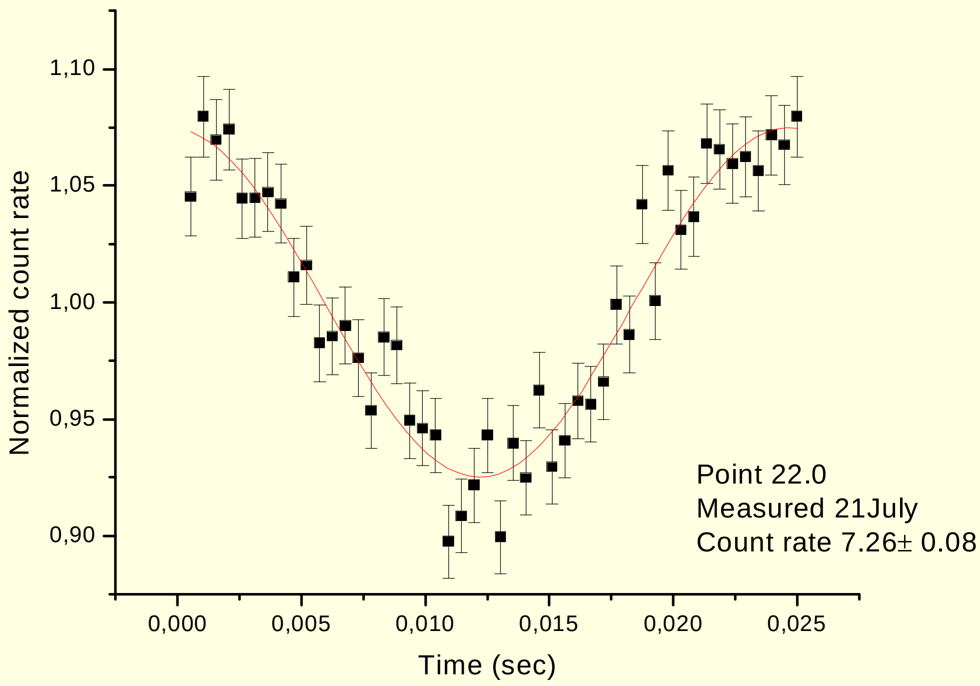




$$\mathbf{P(t)} = \mathbf{1} + \mathbf{A} \cdot \mathbf{sin}(\Omega \mathbf{t} + \varphi) \longrightarrow \mathbf{P(t)} = \mathbf{1} + \mathbf{A} \cdot \mathbf{sin}\left[\Omega\left(\mathbf{t} + \frac{\mathbf{H}}{\mathbf{v}}\right) + \varphi\right]$$

$$\mathbf{T} = \frac{2\pi}{\Omega} = \mathbf{25ms}$$

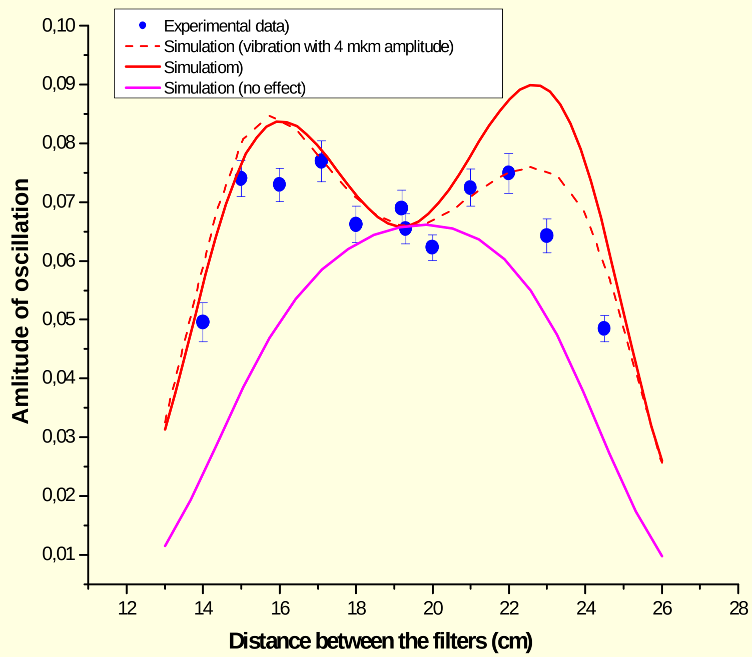
$$\frac{\mathbf{H}}{\mathbf{v}} \approx \mathbf{140ms}$$

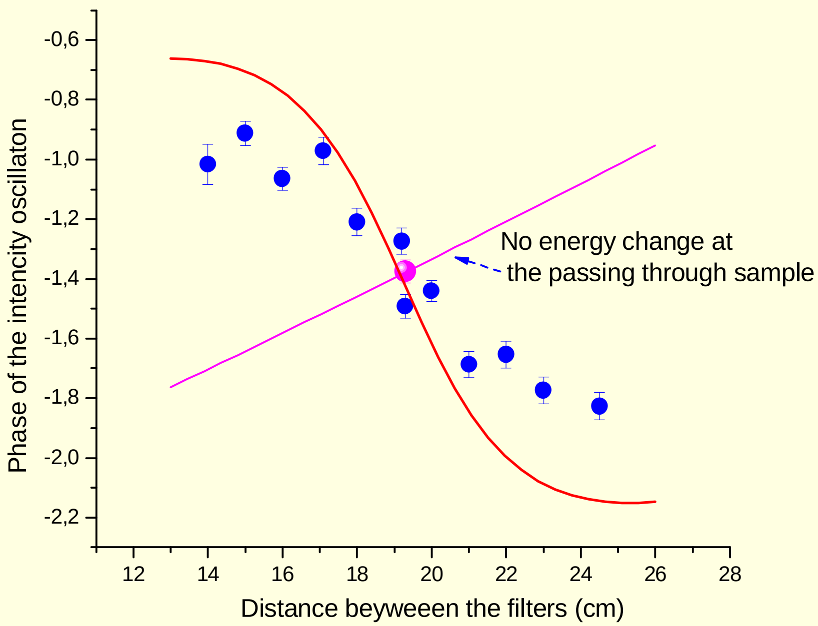
# Oscillation of the count rate




$$f(t) = 1 + A\sin(\Omega t - \varphi)$$

# Experimental results



# Conclusion

1. **Experimental results are in qualitative agreement with theory – neutron changes its energy when passing through an accelerating sample**
2. **There are not quantitative agreement with theory**
3. **The reasons of the discrepancy are still incomprehensible.**

***Thank you for your attention!***

# Wave function

$x(t)$

$$\Psi_0 = e^{i(k_0 x - \omega_0 t)}$$

$$\Psi_f \cong e^{i(k_0 x - \omega_0 t)} e^{\left\{ -\frac{i}{h} m\left(v_0 - \sqrt{v_0^2 - v_b^2}\right)\left[ x(t) - x\left( t - \frac{L}{\sqrt{v_0^2 - v_b^2}} \right)\right]\right\}}$$

$$\varepsilon_f - \varepsilon_0 \cong m\left(v_0 - \sqrt{v_0^2 - v_b^2}\right)\left[\frac{dx}{dt}(t) - \frac{dx}{dt}\left(t - \frac{L}{\sqrt{v_0^2 - v_b^2}}\right)\right] \qquad \varepsilon(t) >> \frac{h}{t}$$

# Test of the vibration