Precise UCN Spectrometry With Fabry-Perot Interferometers

A.I. Frank

I.M. Frank Laboratory of Neutron Physics, JINR

Dubna. Russia

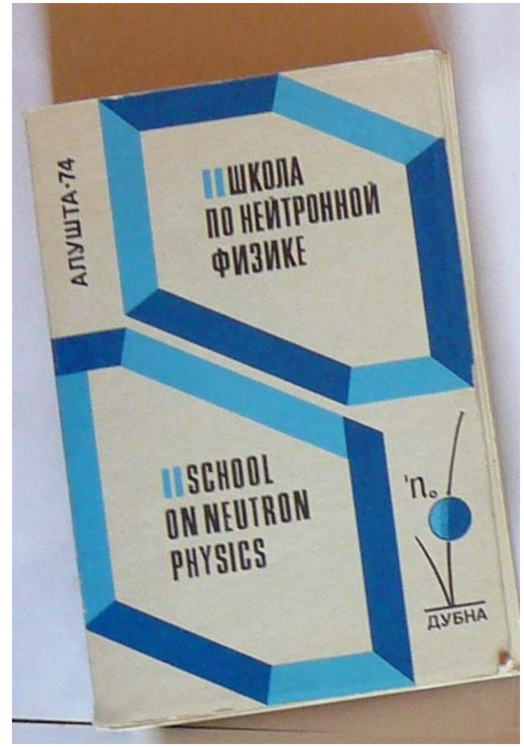
frank@nf.jinr.ru

ISINN 20. Alushta, Crimea

Schools on Neutron Physics, Alushta, Crimea. 1969 – 1990

I.M. Frank

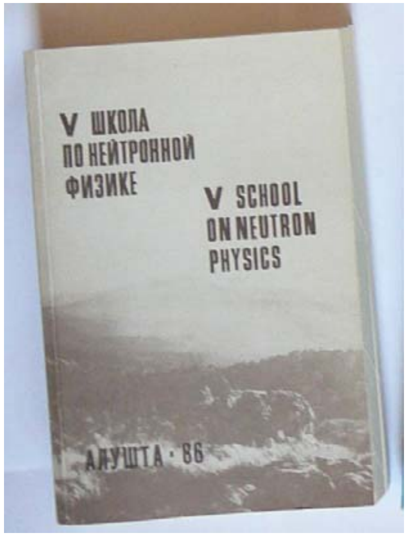
I.M. Frank and F.L. Shapiro



II School, April, 1974

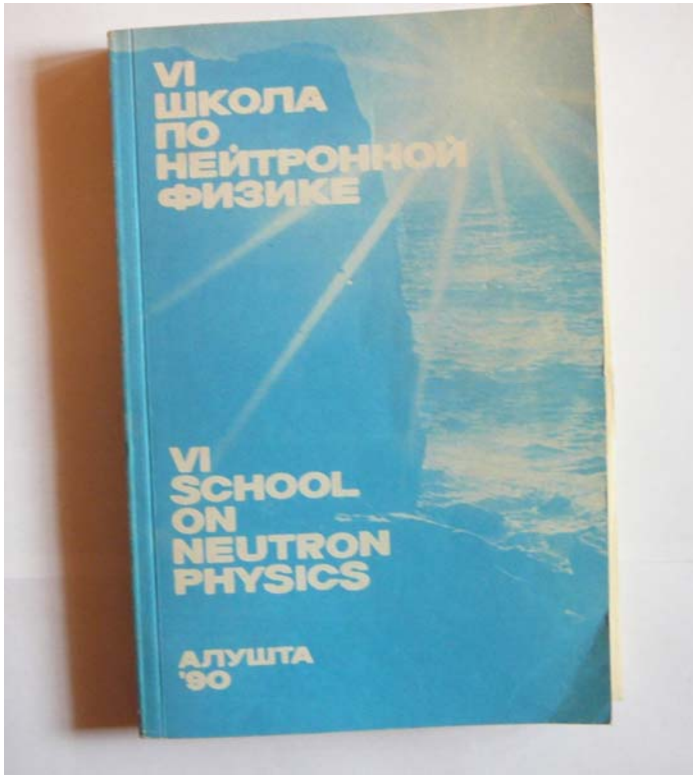
Lectures

1. ***V.I. Luschikov. Storage of ultra cold neutrons***
2. ***I.M. Frank. Neutron optics and ultra cold neutrons***
3. ***A.Steyerl. Very cold neutrons - A new tool in condensed matter research***



V School, October , 1986

My lecture on Neutron Microscopy



VI School October 1990

ПИОНЕРСКИЕ РАБОТЫ И.М.ФРАНКА И СОВРЕМЕННАЯ ОПТИКА
ДЛИННОВОЛНОВЫХ НЕЙТРОНОВ

А.И.Франк

Институт атомной энергии им.И.В.Курчатова, Москва

Эта лекция носит мемориальный характер и появление ее связано с печальным событием – кончиной 22 июня Ильи Михайловича Франка.

29 июня в Лаборатории нейтронной физики ОИЯИ – Лаборатории Франка, коллеги и ученики И.М. провели однодневный семинар, посвященный его памяти. Доклад, прочитанный там, и лег в основу этой лекции.

Pioneering works of I.M.Frank and Modern optics of the Long wave neutrons

Precise UCN Spectrometry With Fabry-Perot Interferometers

1997 - 2011

Overview

- ***FP interferometers and other multilayers structures for UCN spectrometry***
- ***Gravity UCN spectrometer with FP interferometers***
- ***Moving grating as a nonstationary device***
- ***Neutron focusing in time***
- ***Accelerating medium effect***
- ***Test of the weak equivalence principle for neutron***

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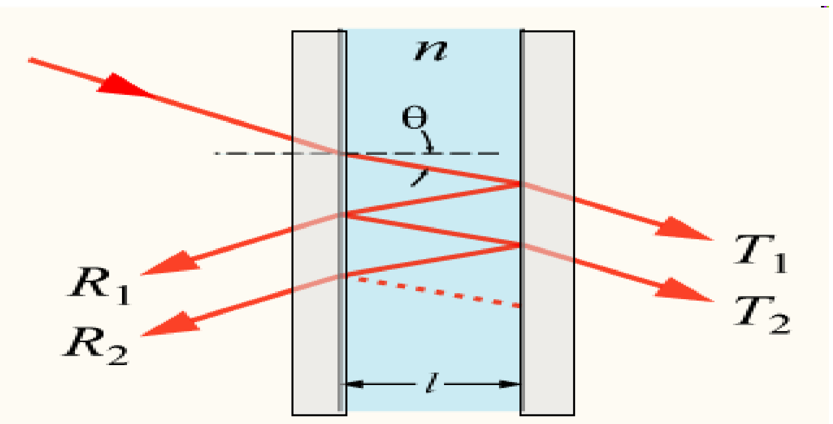
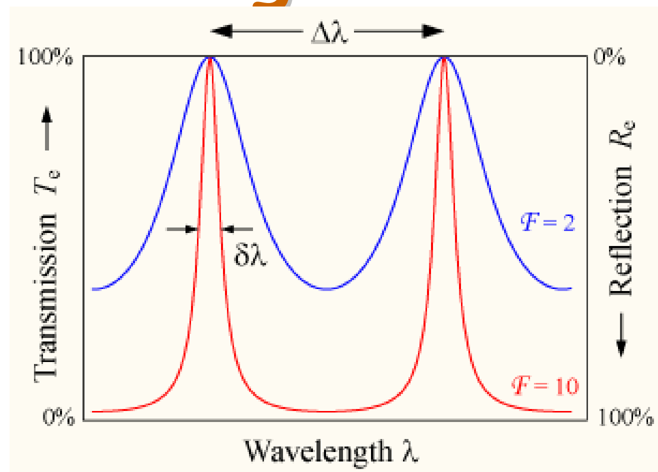
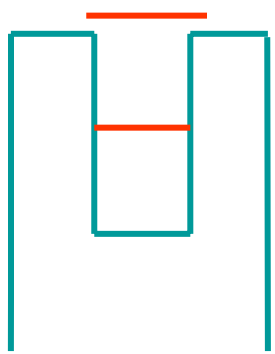
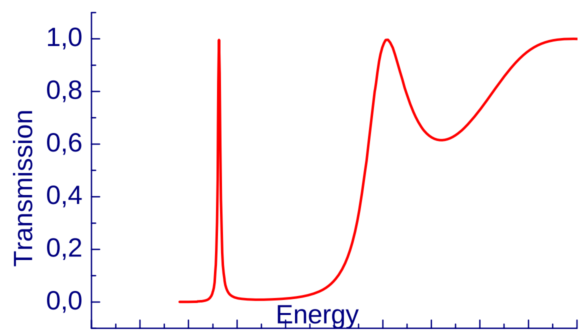
Fabry Perot interferometer for light and its quantum analog



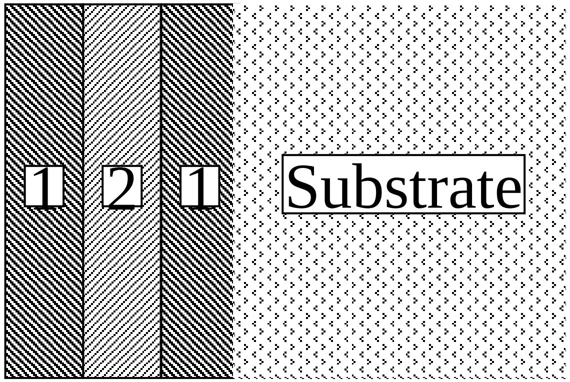


Quantum state





Fabry Perot interferometer (Neutron Interference filter)

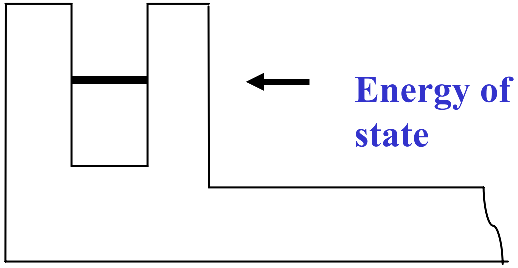


$$U_{1,2} = \frac{2\pi\hbar^2}{m}(\rho b)_{1,2}$$

U ≈ 10^{-7} eV

↓

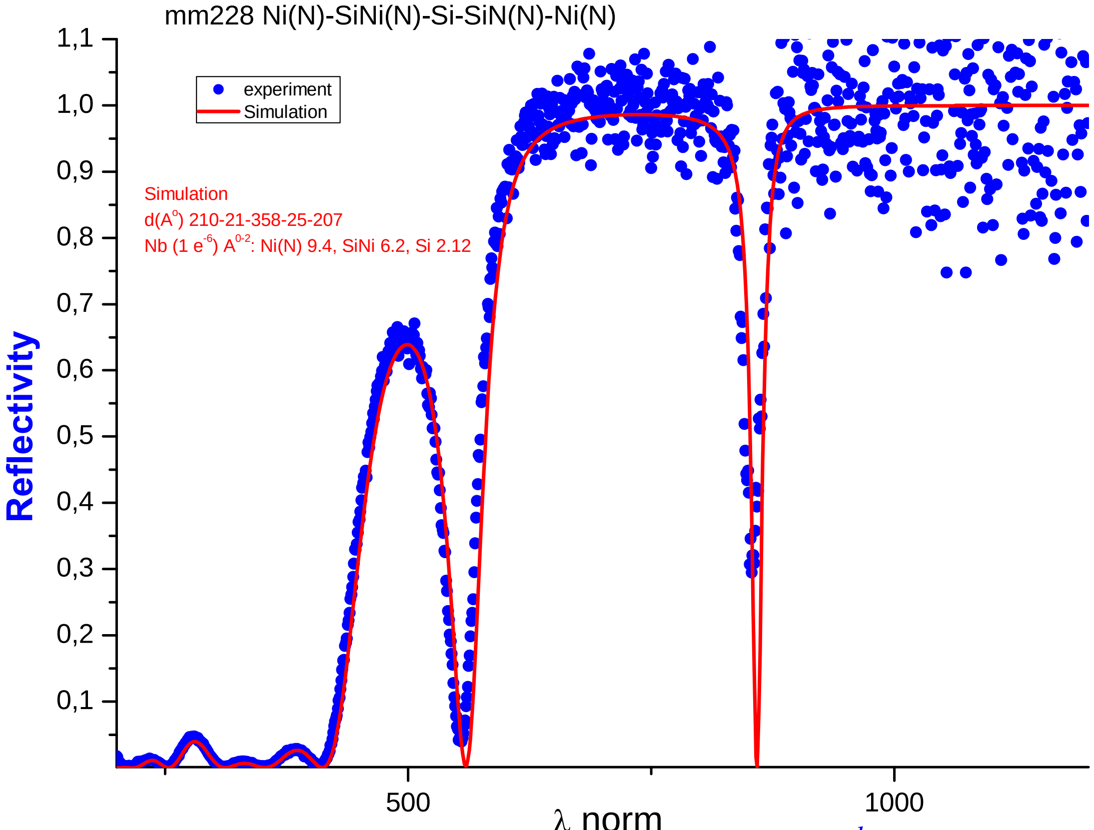
V ≈ 5 m/s



Energy of the state

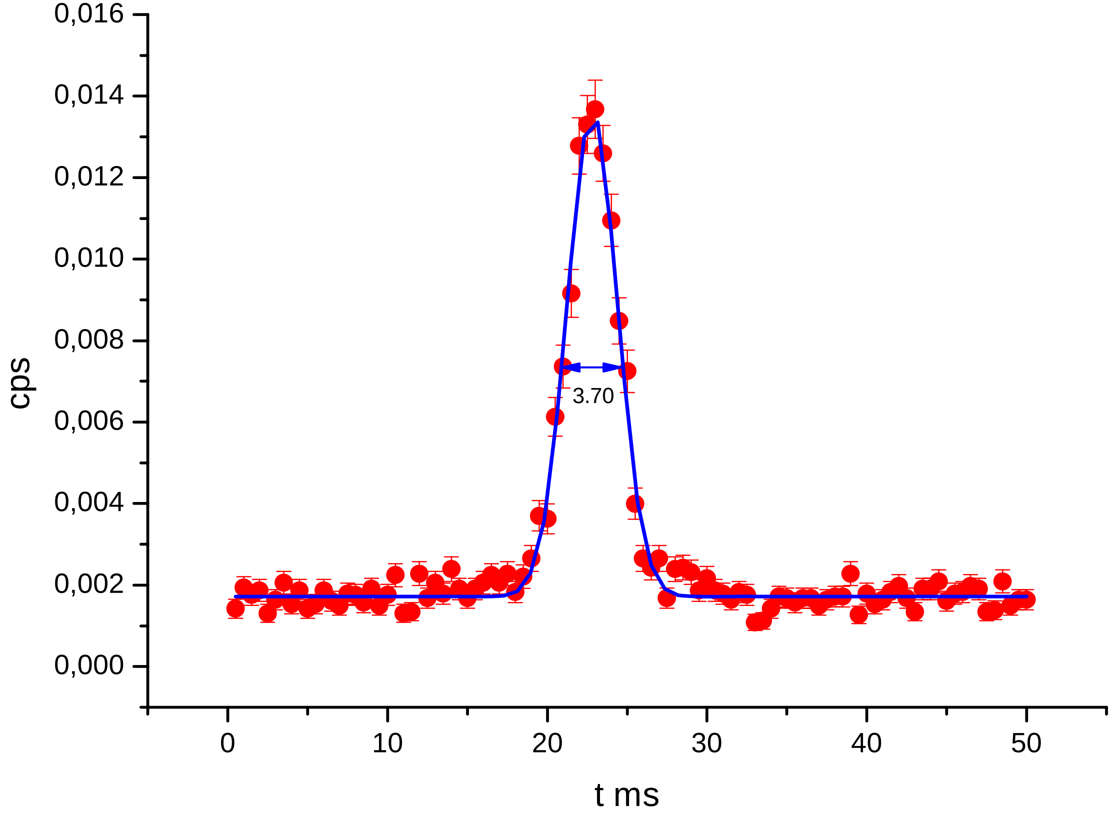
1. A.A. Seregin, Sov. Phys. JETP 46 (1977), p. 859.
2. M.I.Novopoltsev et al.NIM A. 264 (1988) P.518.
3. A. Steyerl, et al, PhysicaB 151 (1988) 36.
4. Bondarenko I.V., Frank A.I., Balashov S.N.et al. J.Phys. Soc. Jpn. 65(1996). Suppl. A. P.29.

First test at the IBR2 reactor, Dubna (neutron reflectometer “Reflex”,1997)



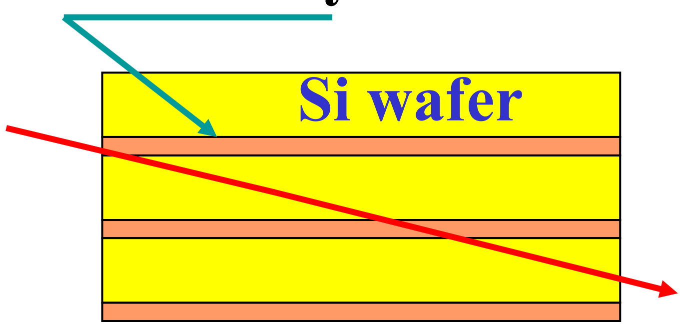
$$\lambda_{norm} = \frac{\hbar}{mv_{\perp}}$$

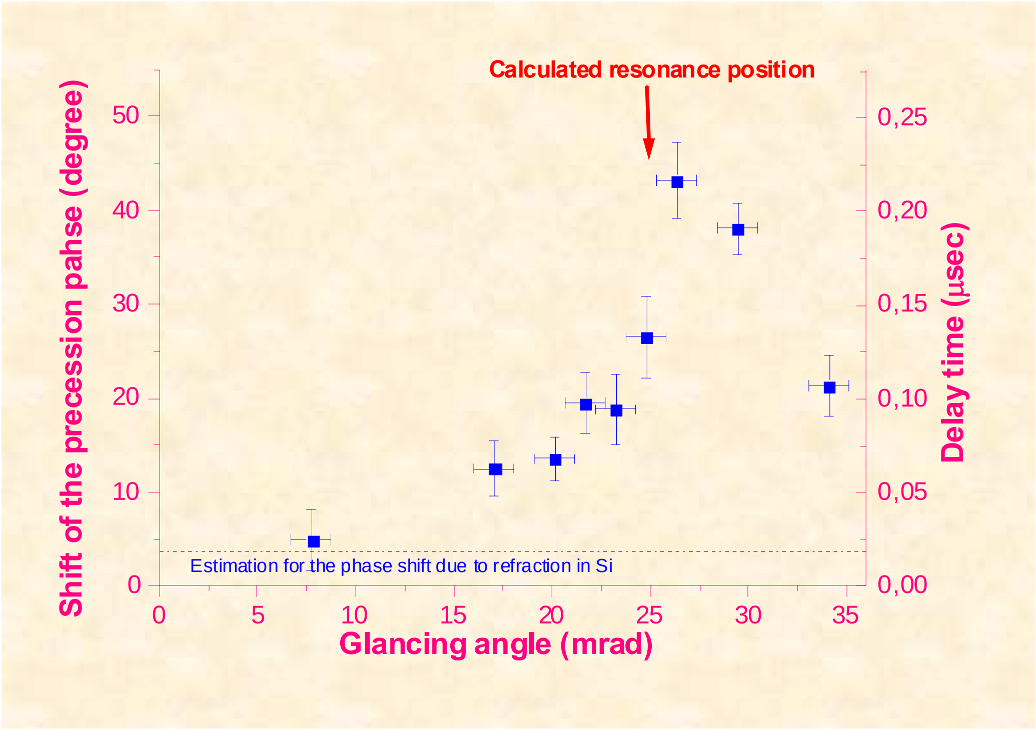
I.V.Bondarenko et al, Physics of Atomic Nuclei, 62 (1999), p.721-737.



TOF spectrum of the UCN passed through FPI.
Total time ~ 140 ms. (2011 г)

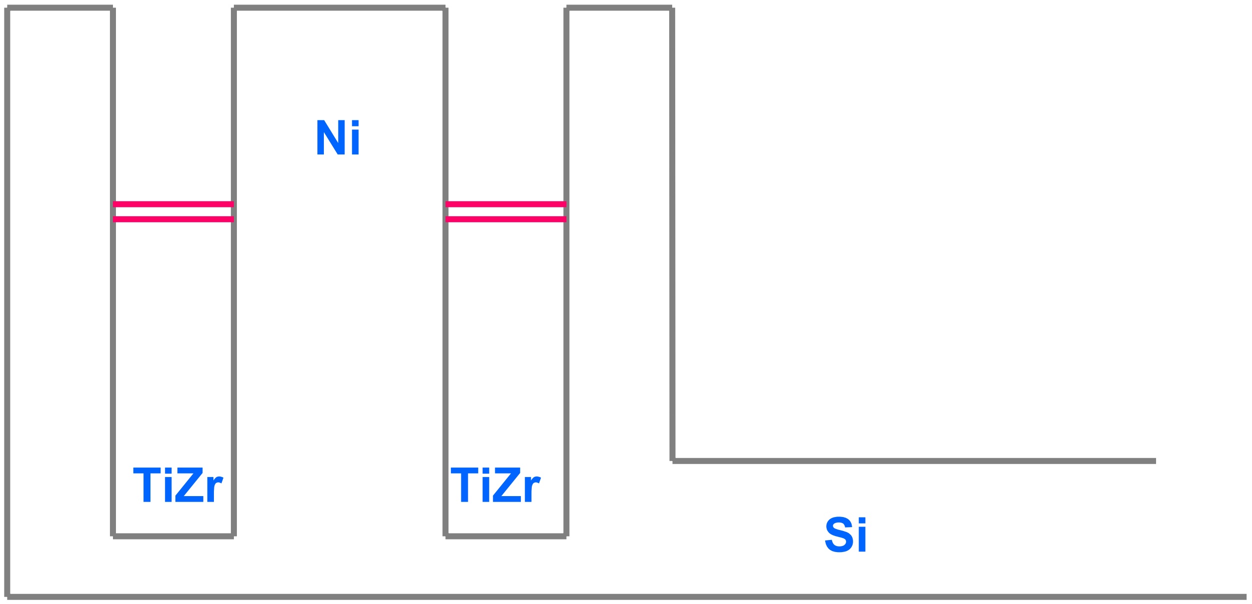
Delay time at resonant tunneling (Larmor clock, 1997)



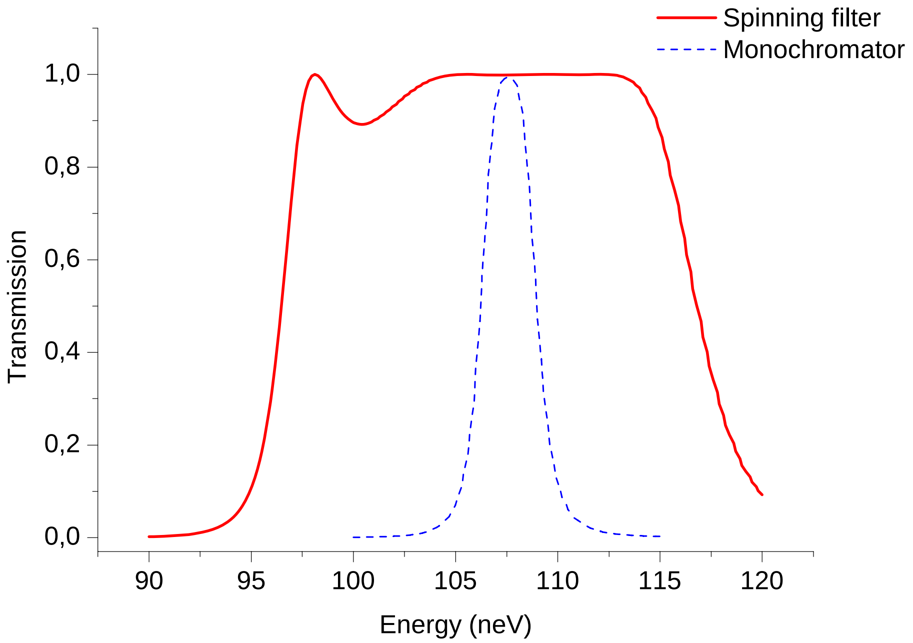


A.IFrank, I.V.Bondarenko, V.V.Vasil'ev et al. JETP Letters, 75, 705 (2002).

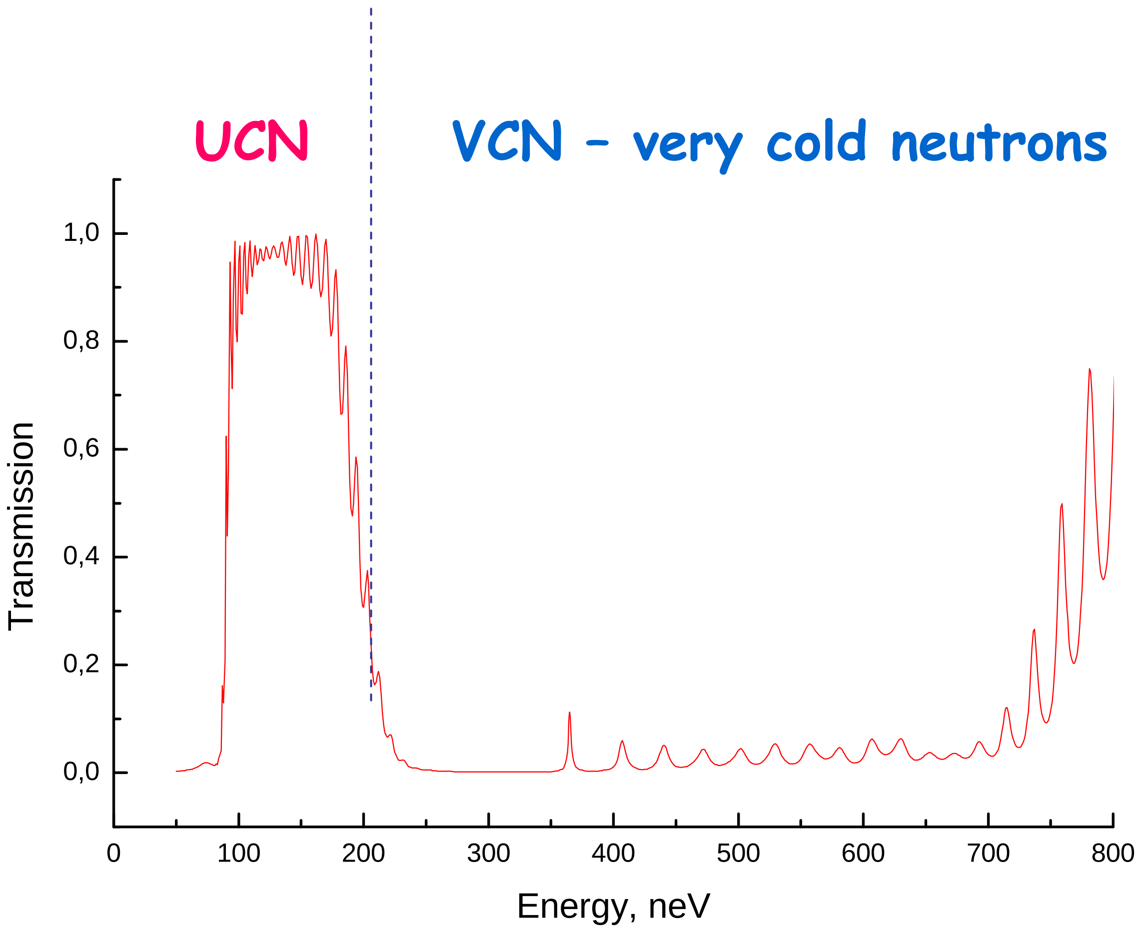
Potential structure of the 5 -layers FP interferometer



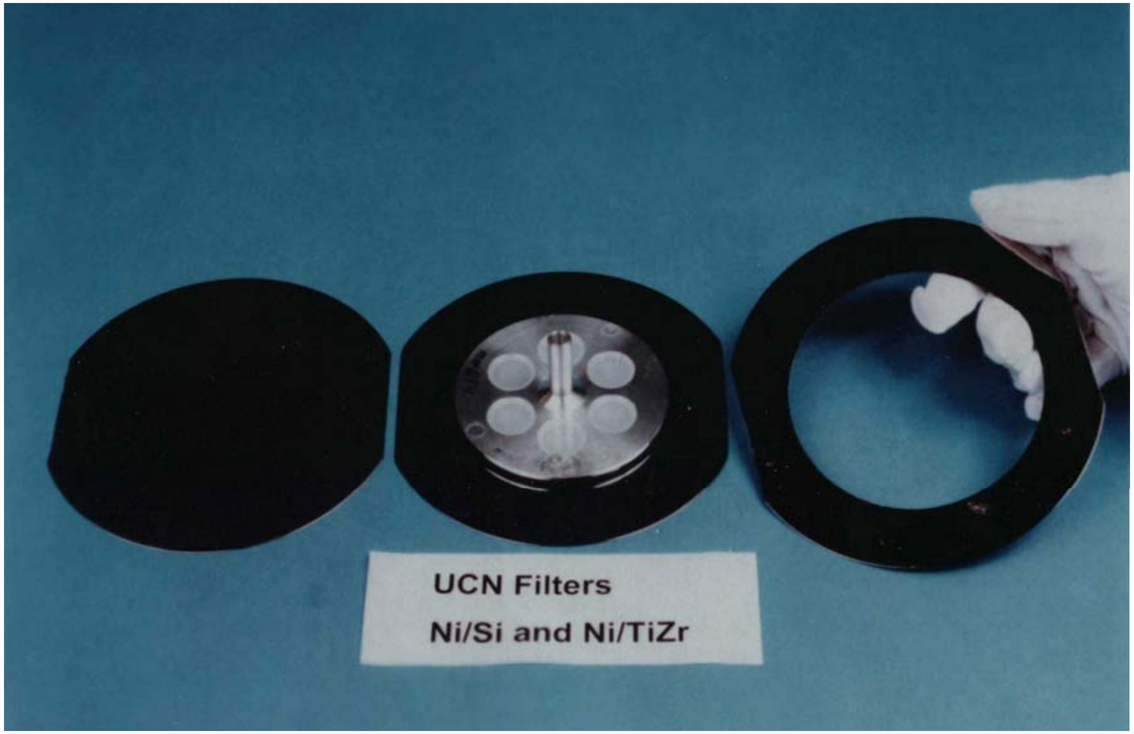
9-layers structure (wide window)



Multi- layers "superwindow" - supermirror + antireflecting structure (>110 layers)



Neutron Fabry –Perot interferometers (Interference filters)



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

- ***FP interferometers and other multilayers structures for UCN spectrometry***
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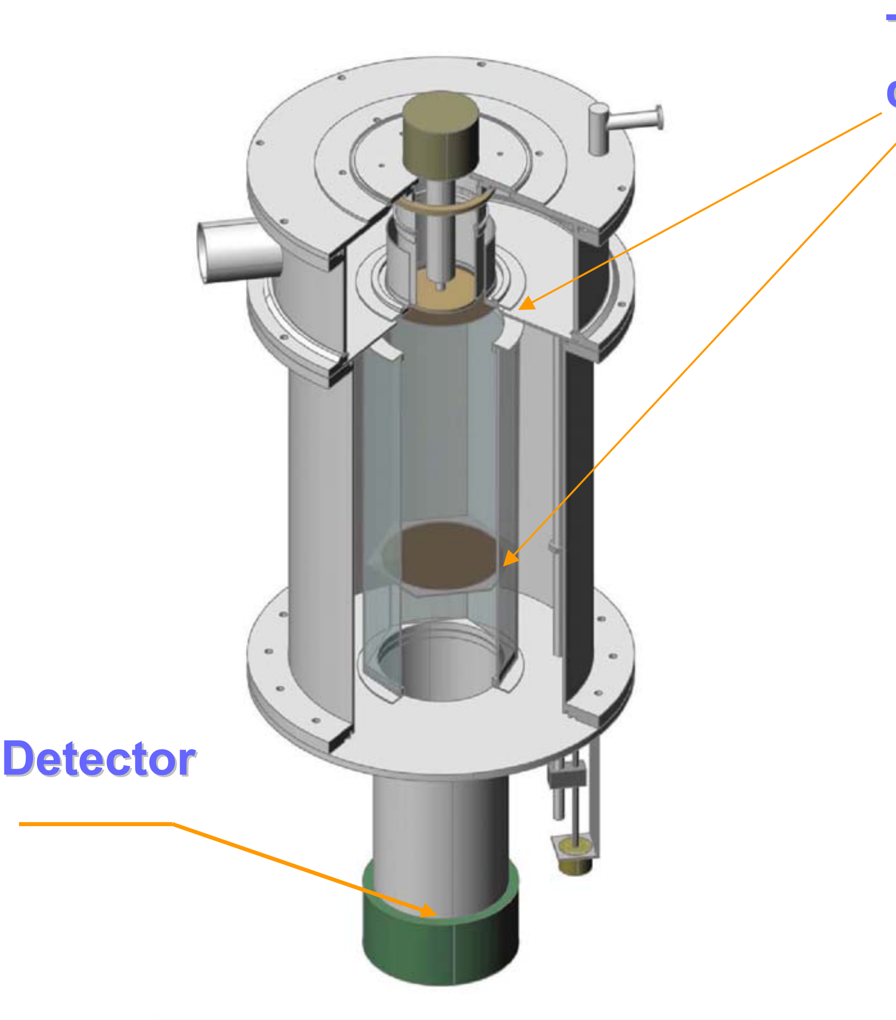
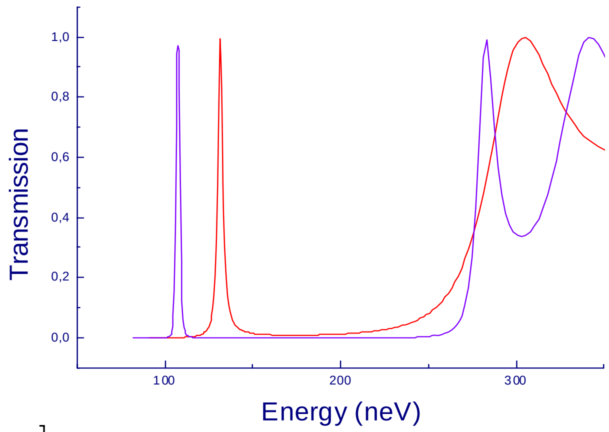
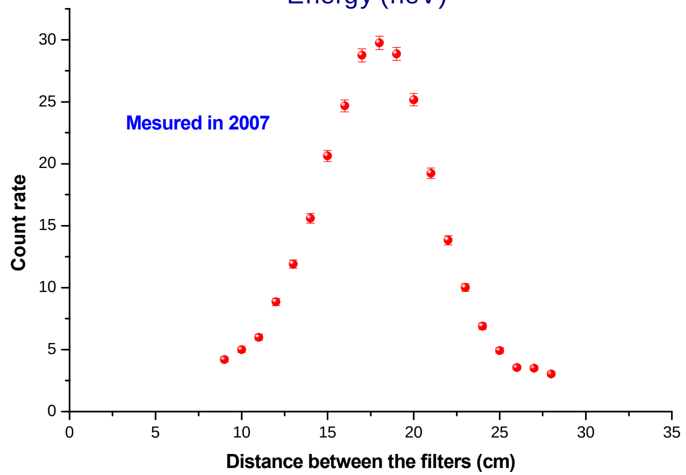
UCN spectrometer with Fabry-Perot interferometers



mg=1.02 neV





A.I.Frank. ISINN 20, Alushta, Crimea, 22 May 2012г

FLNP

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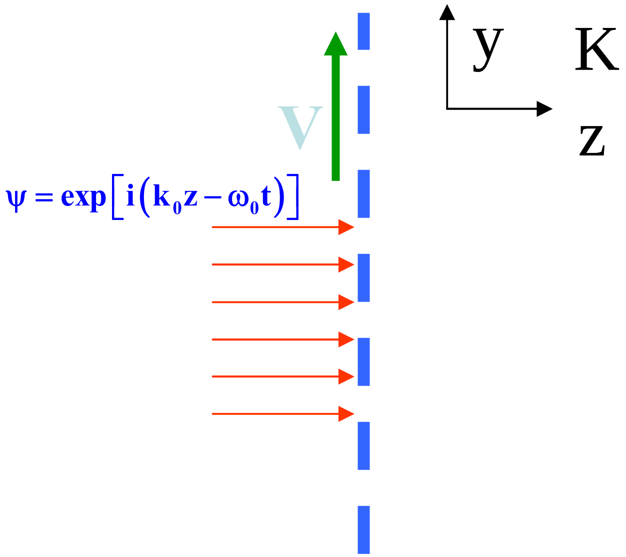
Elementary theory

A.Frank, V.Nosov, 1994



1. Solution of a diffraction problem in a moving system of reference.

2. Galilean transformation of the wave function.

$$\Psi(z,y,t) = \sum_j a_j \exp[i(k_j z + q_j y - \omega_j t)]$$

$(k_0 L << 1)$

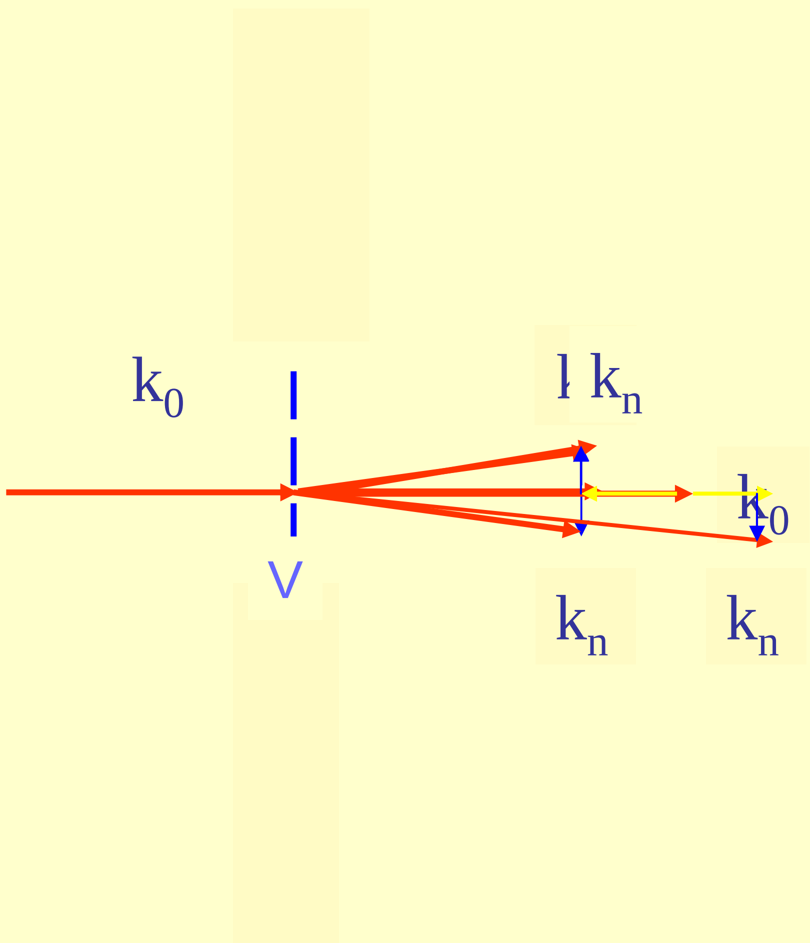
$q_j = j \cdot \left(2\pi / L\right) = j q_0$

$$\omega_j = \omega_0 + j\Omega \qquad k_j \cong k_0 \left(1 + j\frac{\Omega}{\omega_0}\right)^{\frac{1}{2}} \qquad j = 0, \ \pm 1, \ \pm 2....$$

$$\Omega = \frac{2\pi}{T} = 2\pi f = 2\pi \left(\frac{V}{L}\right)$$

L – Grating space period

Neutron diffraction by a grating at rest and by a moving grating



$$q_0 = \frac{2\pi}{L} \qquad |k_0| = |k_n| \qquad \Delta k_{zn} = n q_0$$

$$\omega_n = \omega_0 + n\Omega \qquad k_n = k_0\left(1 + n\frac{\Omega}{\omega_0}\right)^{\frac{1}{2}}$$

In a limit $L \to \infty$, $V \to \infty$,
$V/L = f = const$

Amplitude or phase modulation of the transmitted wave

Moving grating as a quantum modulator

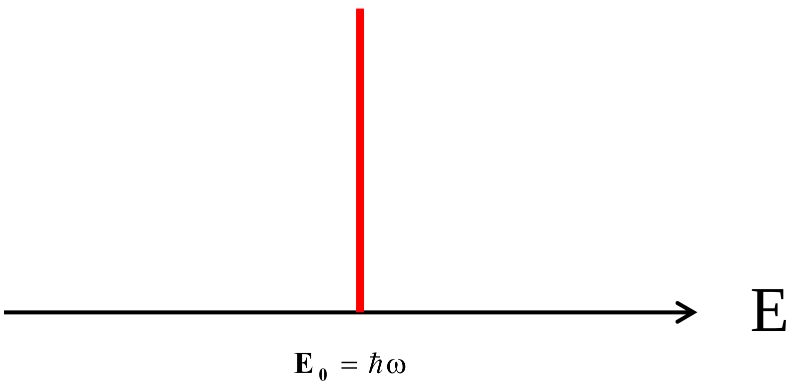
$$\theta(y) = \begin{cases} 1 & \text{if} \quad 0 < y < L/2 \\ \exp(i\pi) & \text{if} \quad L/2 < y < L \end{cases}$$

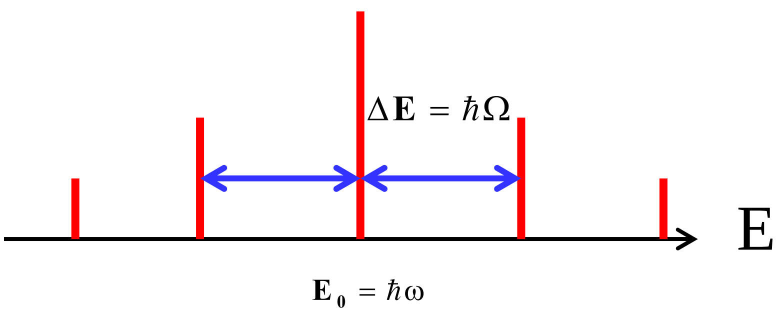
$$a_n = \frac{2}{i\pi n}, \qquad n = 2s - 1$$

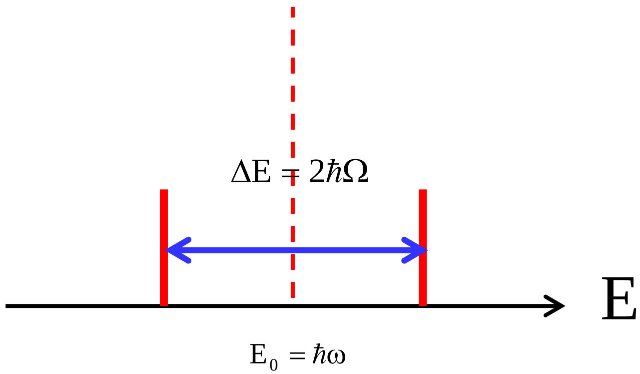
Only odd diffraction orders

$a_0 = 0$!

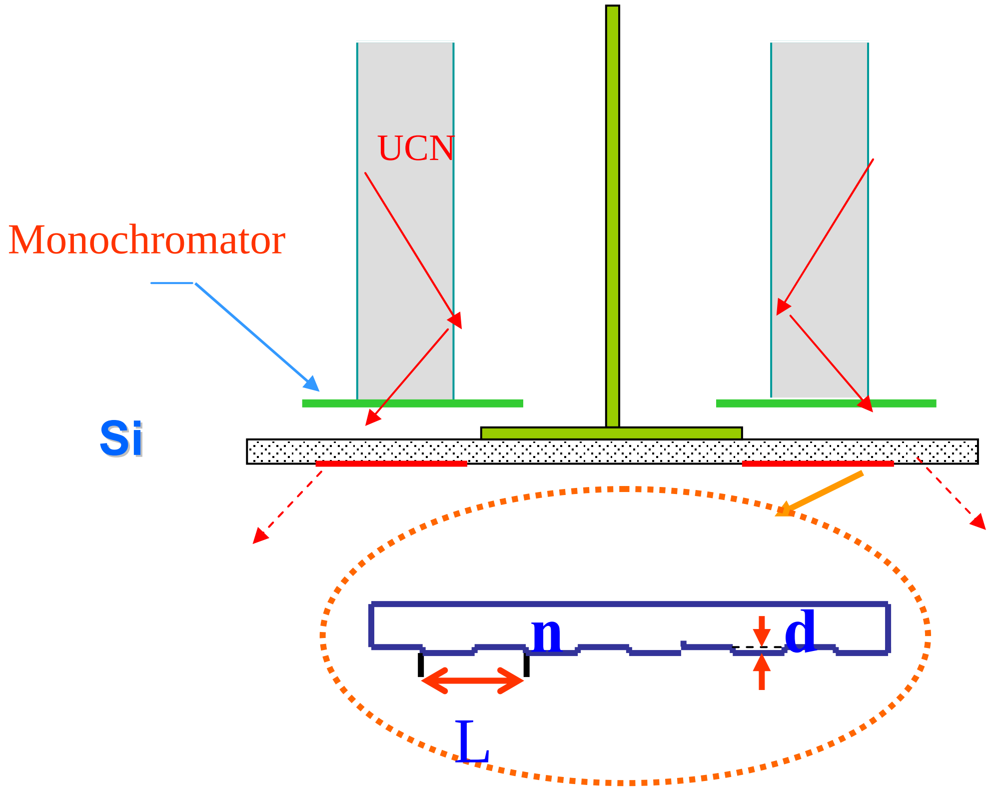
$$|\mathbf{a}_{\pm 1}|^2 = \frac{4}{\pi^2} = 0.403$$

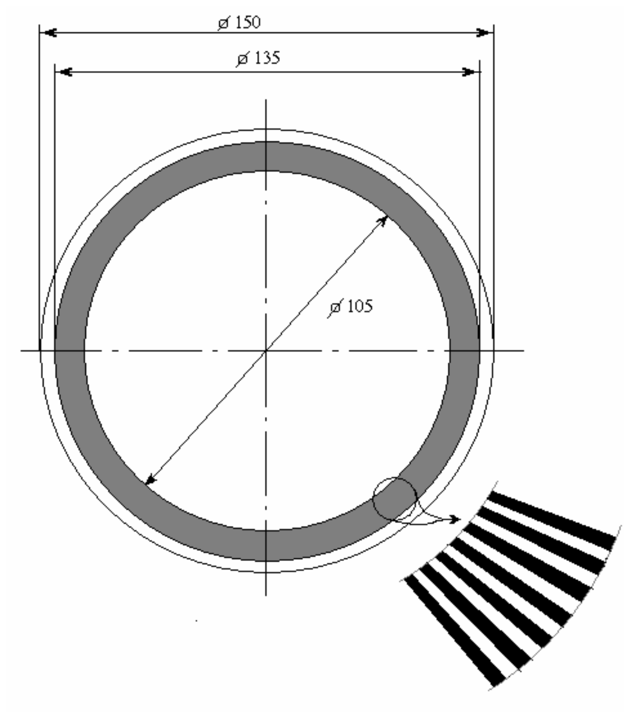






Experimental realization





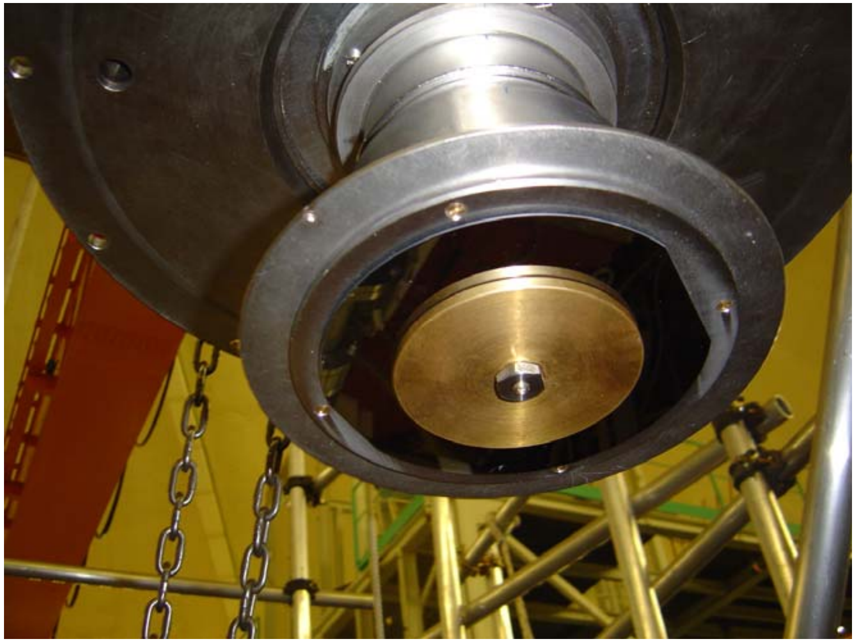
$$\Delta\varphi = \mathbf{k}(\mathbf{n}-1)\mathbf{d} = \pi$$

d=0.14μ

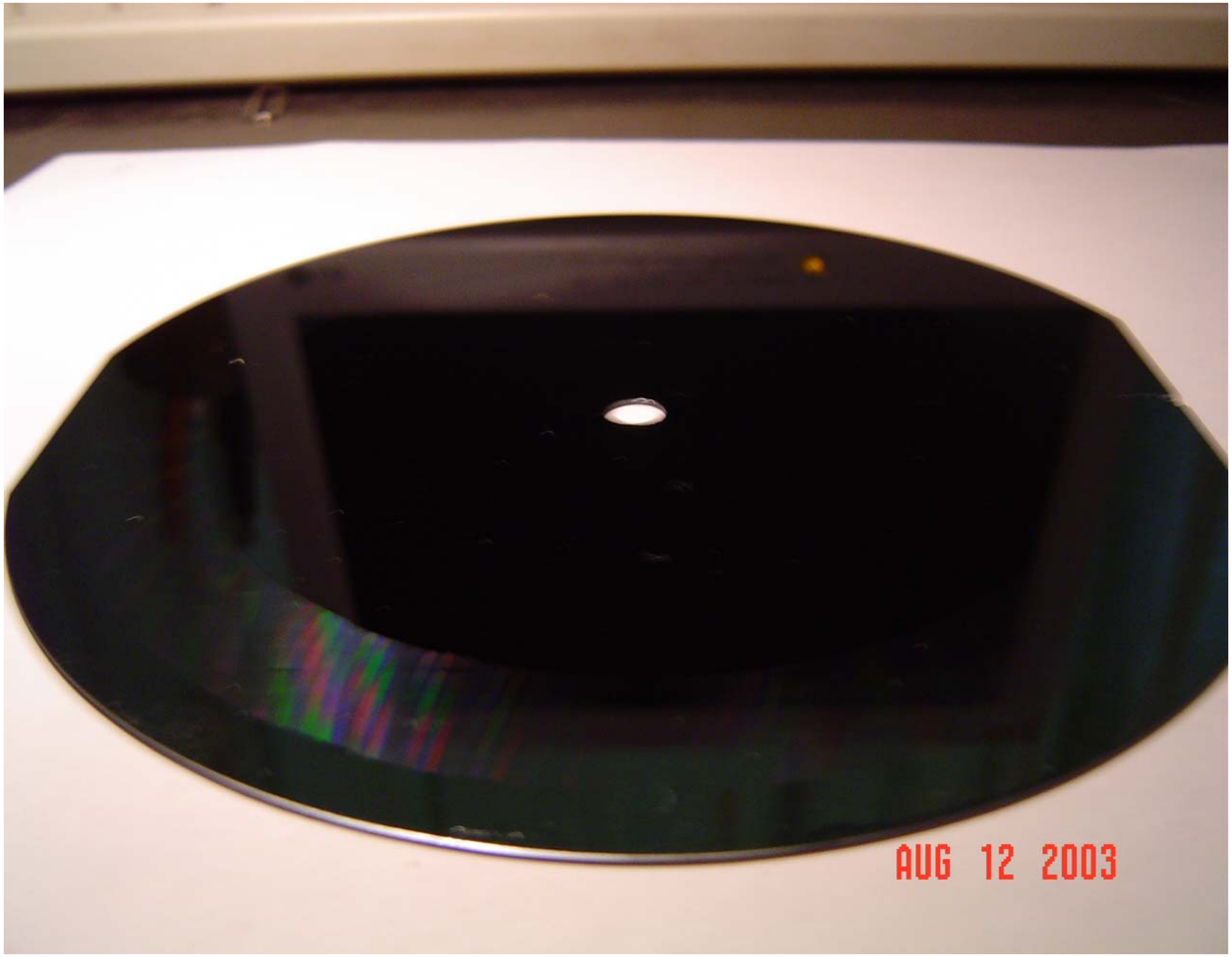
$$\Delta E = \hbar\Omega \qquad \Omega = 2\pi\frac{2\pi fR}{\alpha R} = 2\pi fN$$

where α is an angular period and N – number of groves

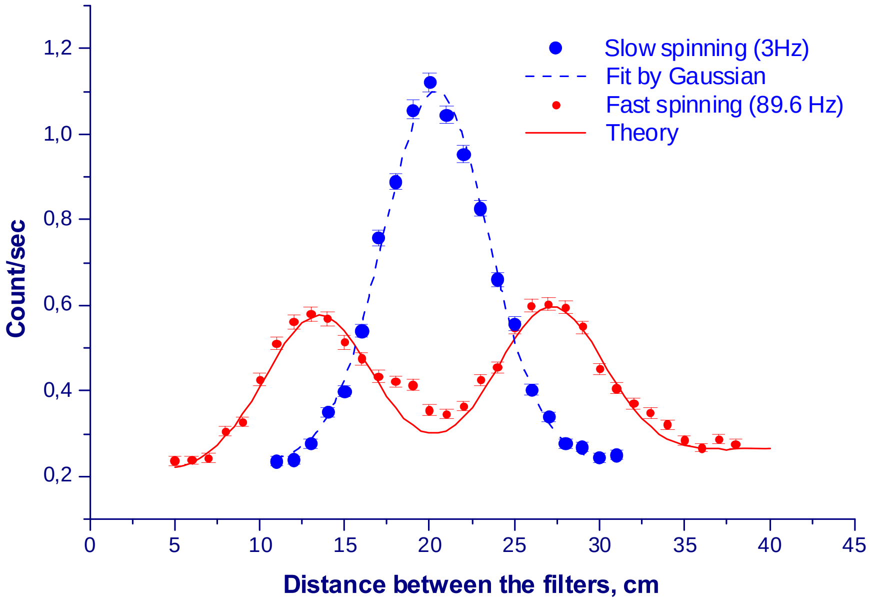
N = 75398

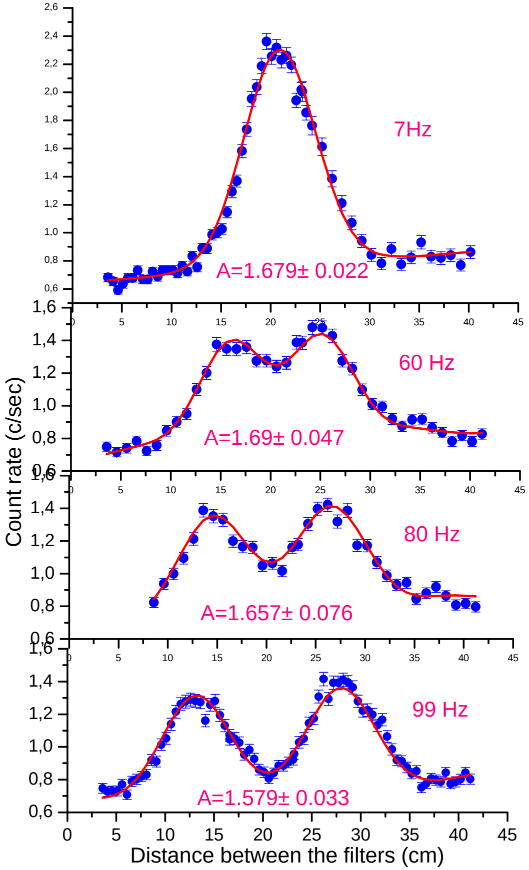



2004


AUG 12 2003

Experimental results





Energy state splitting:

Neutron diffraction by a moving grating
or
phase modulation of a neutron wave

$$\left|a_1\right|^2_{th} = 0.403$$

$$\left|a_1\right|^2_{exp} = 0.383(8)$$

A.I.Frank et al. Phys.Lett.A 311 (2003) 6

Jetp Lett, 81 (2005) 427

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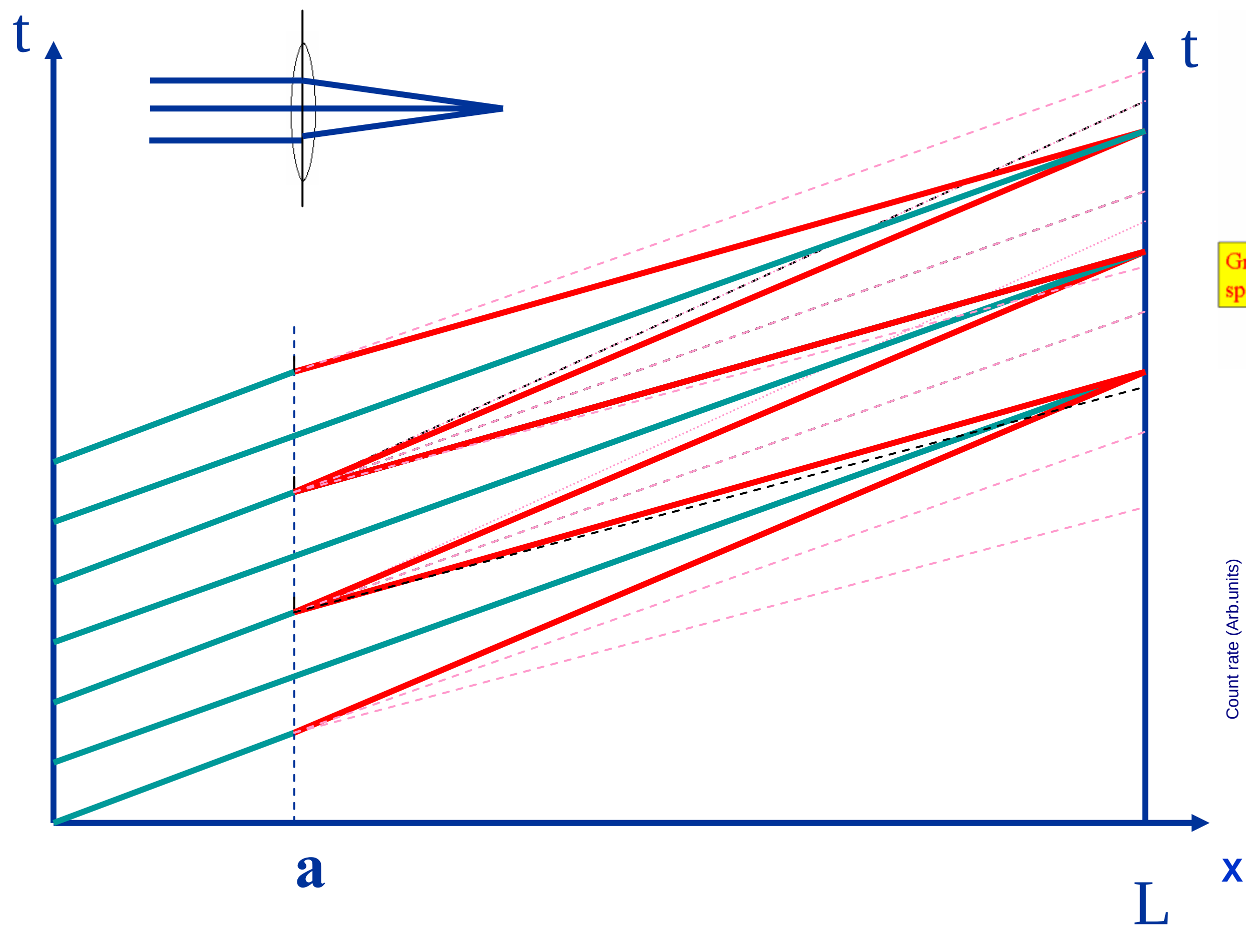
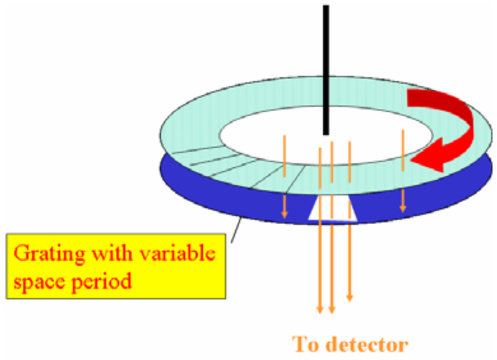
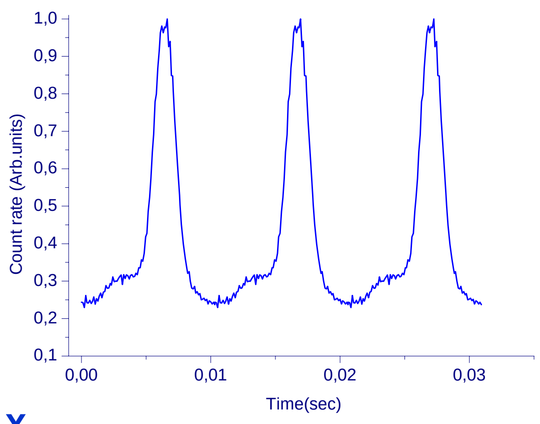
Neutron focusing in time

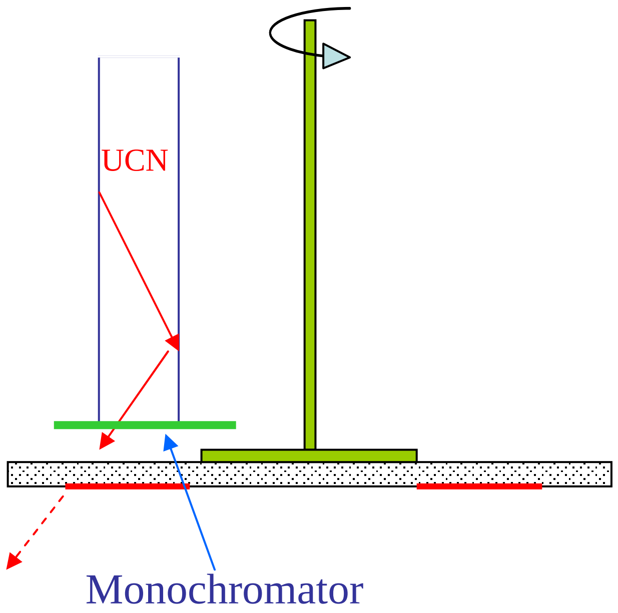


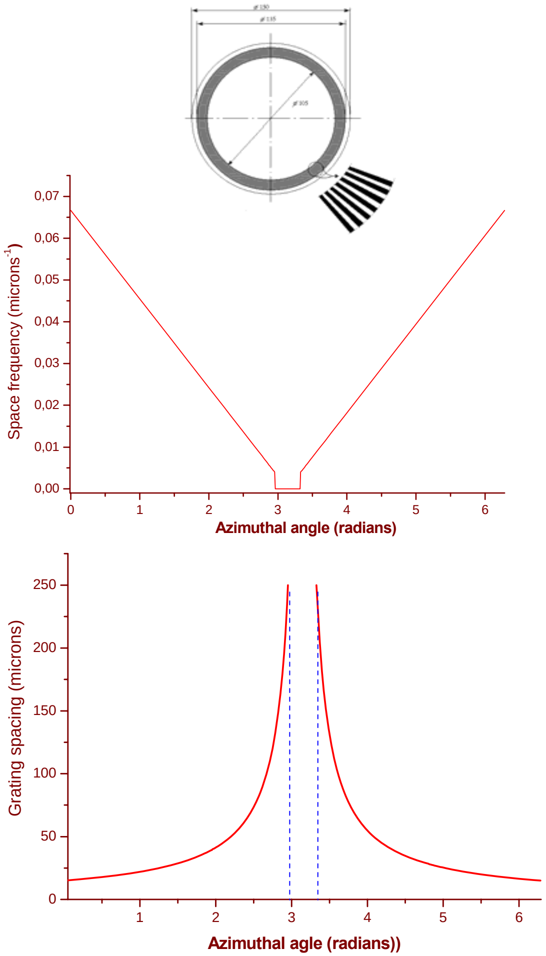


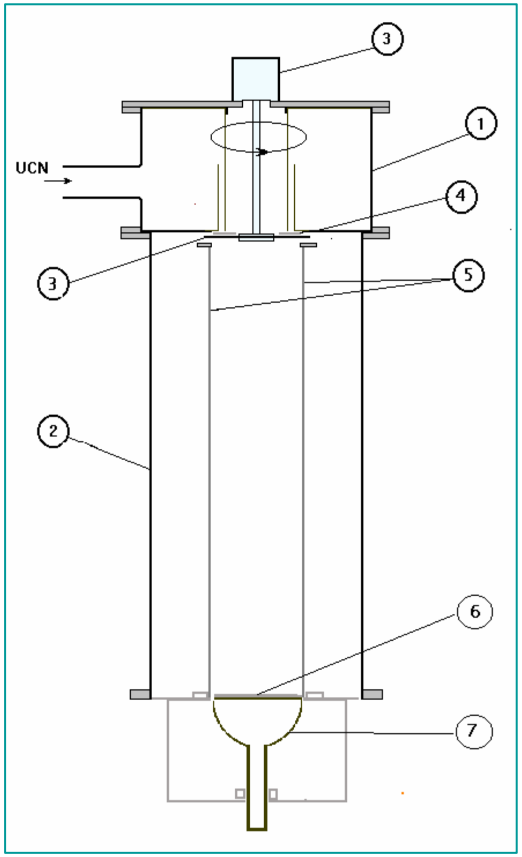


A.I.Frank and R.Gähler. Time Focusing of Neutrons. Physics of Atomic Nuclei, v.63, 2000, pp.545-547

Rotating grating as a time lens







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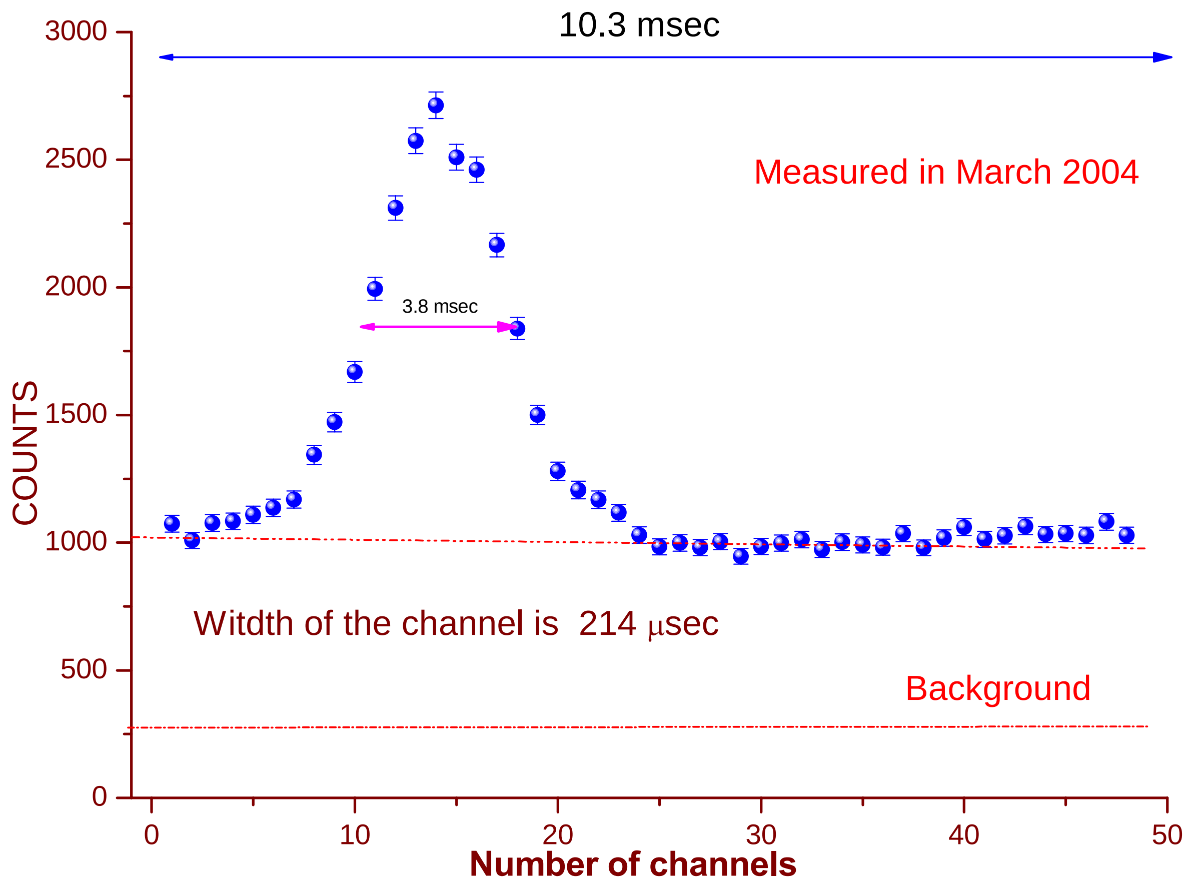
Neutron time lens is working!



A. I. Frank, P. Geltenbort, G. V. Kulin et al. JETP Lett. 78, (2003) 188
S.N. Balashov, I.V. Bondarenko, A.I. Frank et al, Physica B, 350 (2004) 246

- ***FP interferometers and other multilayers structures for UCN spectrometry***
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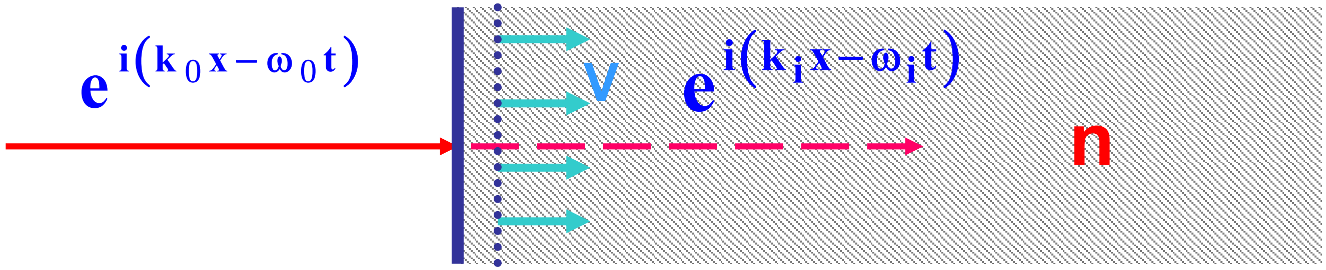
Refraction of wave at the border of the moving matter



$$k_i = nk_0\left(1 + \frac{1-n}{n}\frac{V}{c}\right)$$

$$\omega_i = \omega_0 + (n-1)k_0 V$$

Doppler shift

<u>Light</u>

$$k_0 = \frac{\omega_0}{c} \qquad \left(\frac{V}{c} << 1\right)$$

$$v_{ph} = \frac{c}{n} + v\left(1 - \frac{1}{n^2}\right)$$

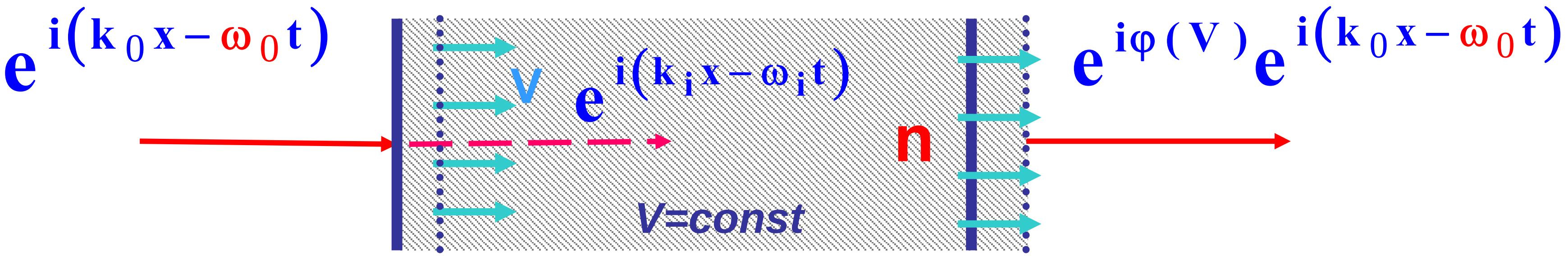
Fresnel drag

<u>Massive particle (neutron)</u>

$$k_0 = \frac{mv_0}{\hbar} \qquad (c \to v_0) \qquad \left(\frac{V}{v_0} << 1\right)$$

$$n \equiv n(k_0') = n(k_0 - k_v)$$

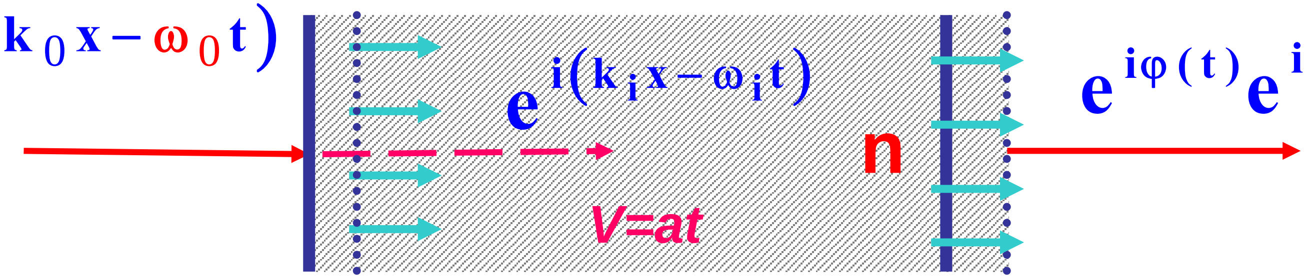
Transmission of a wave through the moving sample (constant velocity)



When the wave enters into the sample from free space, the frequency of the wave suffers frequency shift. When the wave comes out of the medium into free space, the frequency of the wave suffers an inverse frequency shift. For the constant-velocity motion, these two frequency shifts cancel each other.

Transmission of wave through the sample (accelerated motion)

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



$e^{i\varphi(t)} e^{i(k_f x - \omega_f t)}$

$\omega_f \neq \omega_0$

For the constant-velocity motion, two frequency shifts cancel each other because the velocity at the time when the wave enters into the medium equal to that at the time when the wave comes out of the slab. For the accelerated motion, two frequency shifts do not cancel because the velocity of the medium is not constant.

Accelerating medium effect in neutron and light optics

Neutrons

$$\Delta E \cong maL\left(\frac{1}{n}-1\right)$$

F.V.Kowalski, Phys. Lett. A, 182 (1993) 335,
V.G.Nosov, A.I.Frank. Phys. At. Nuclei, 61, (1998) 613

Light

$$\Delta\omega \cong \frac{\omega a L}{c^2}(n-1)$$

K. Tanaka, Phys. Rev . A, 25 (1982) 385,

A.I. Frank, P.Geltenbort, G.V.Kulin, et al, Phys. At. Nuclei, 71 (2008) 1656.

UCNs

Si L ≈ 0.6 mm, a ≈ 10 g

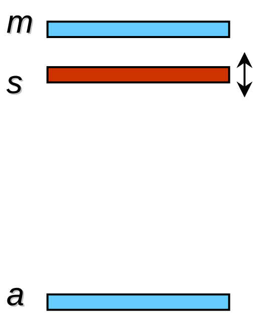
$$\frac{\Delta E}{E} \approx 3\times10^{-3}$$

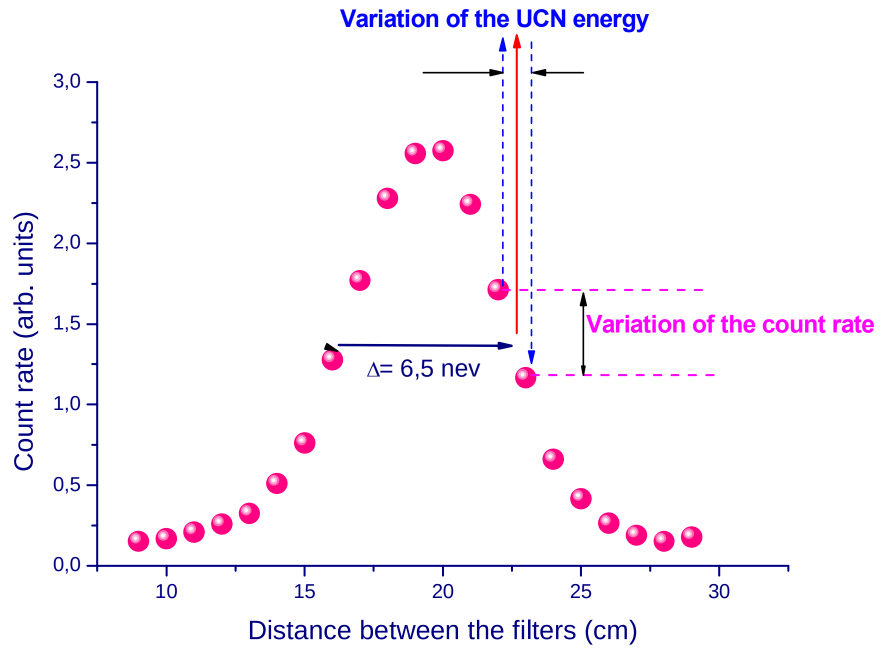
L ≈ 1m, a ≈ 10 g

$$\frac{\Delta\omega}{\omega} = 5\times10^{-15}$$

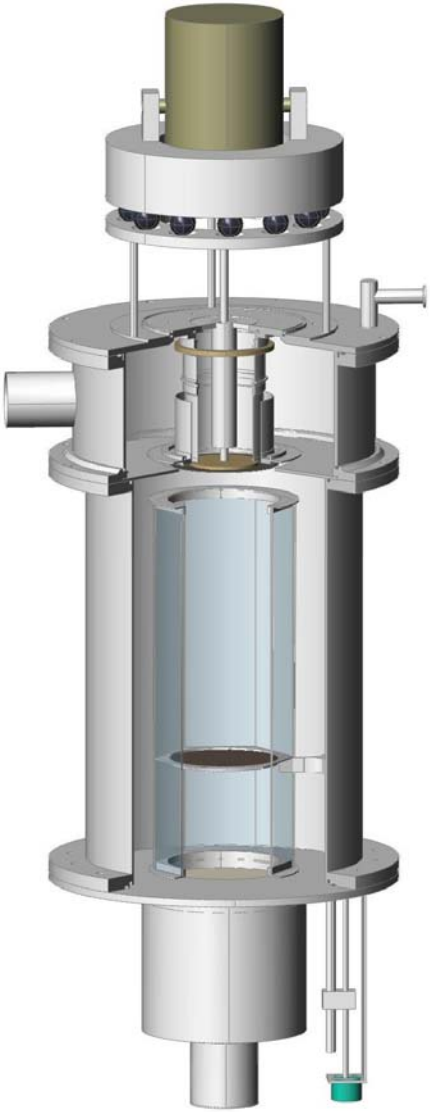
A.I.Frank. ISINN 20, Alushta, Crimea, 22 May 2012г

Idea of the spectrometric experiment



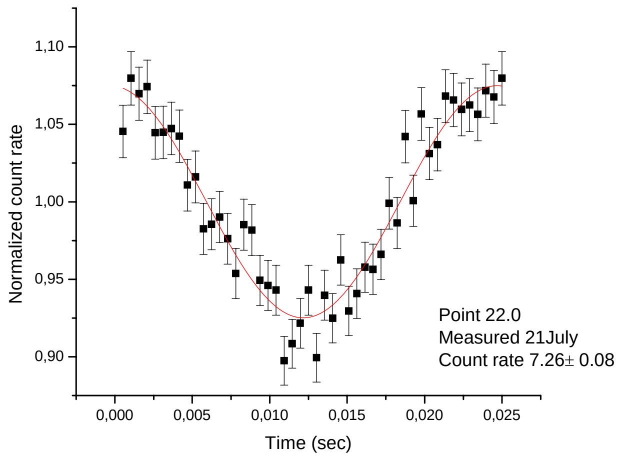


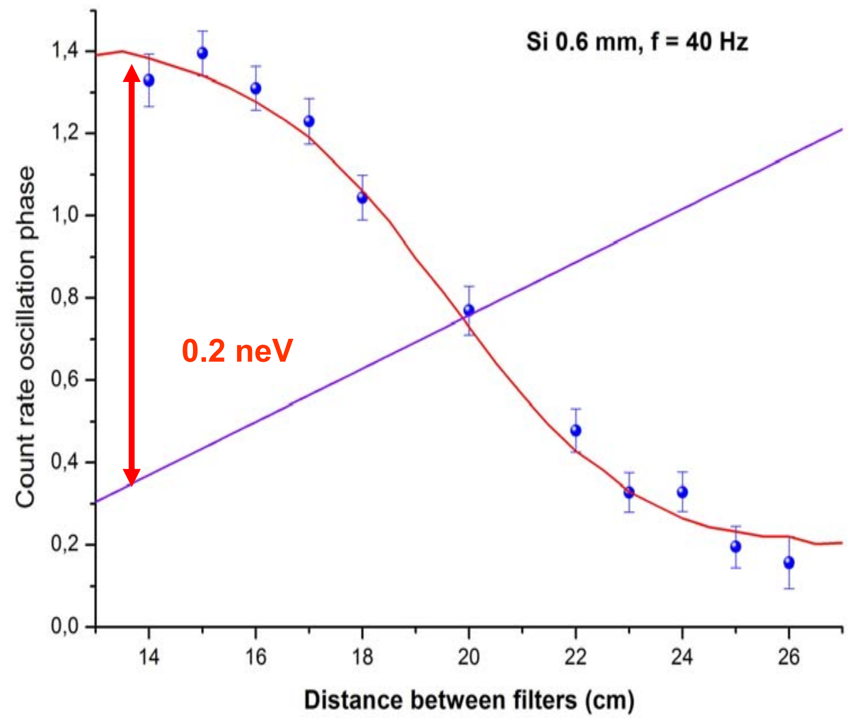
Periodically variation of the neutron energy, caused by the sample acceleration, leads to the periodical oscillation of the count rate




2005

Oscillation of the count rate and exper…





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

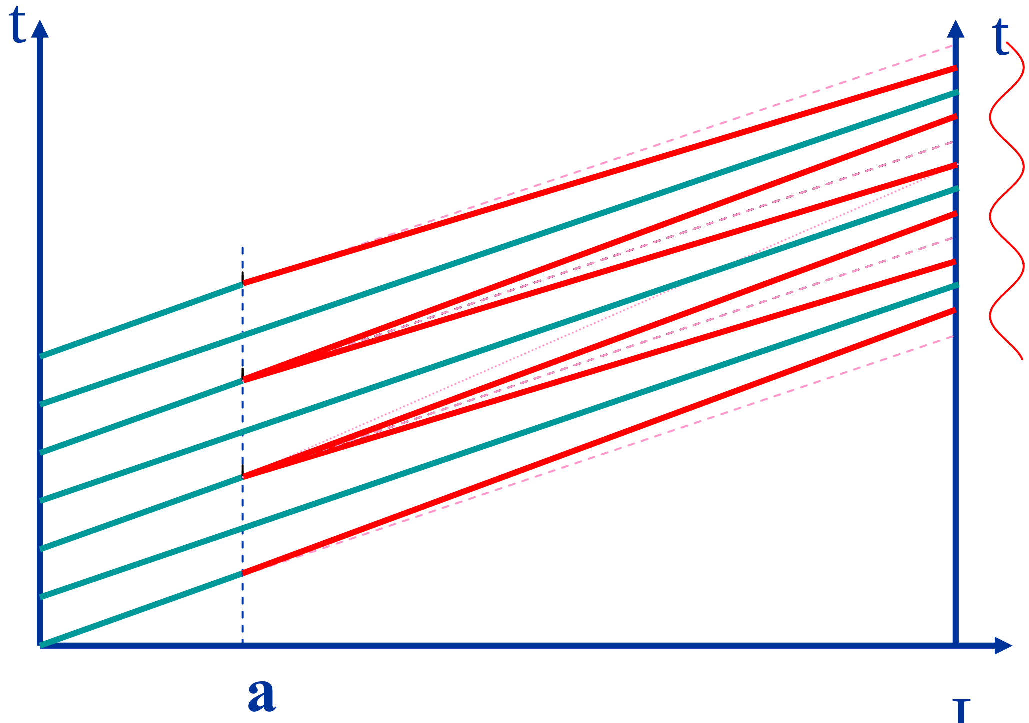
Frequency f = 40, 60 Hz
Oscillation period 0.025, 0.017 sec
Time of flight 0.11 sec

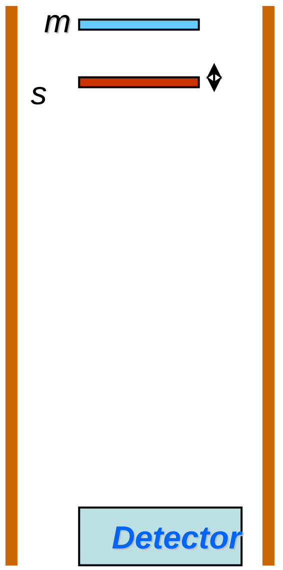
$$\Delta E \cong -K m A \Omega^2 L \left(\frac{1}{n} - 1\right) \sin \Omega t$$

$$K = 0.94 \pm 0.06$$

A.I. Frank, P.Geltenbort, G.V.Kulin, et al, Phys. At. Nuclei, 71 (2008) 1656.

Weak focusing in time and Accelerating Medium Effect





$$\frac{\Delta V_{exp}}{\Delta V_{th}} = 0.92 \pm 0.08_{stat} \pm 0.02_{syst}$$

$$a_{max} = A\Omega^2 = 57 m/s^2$$

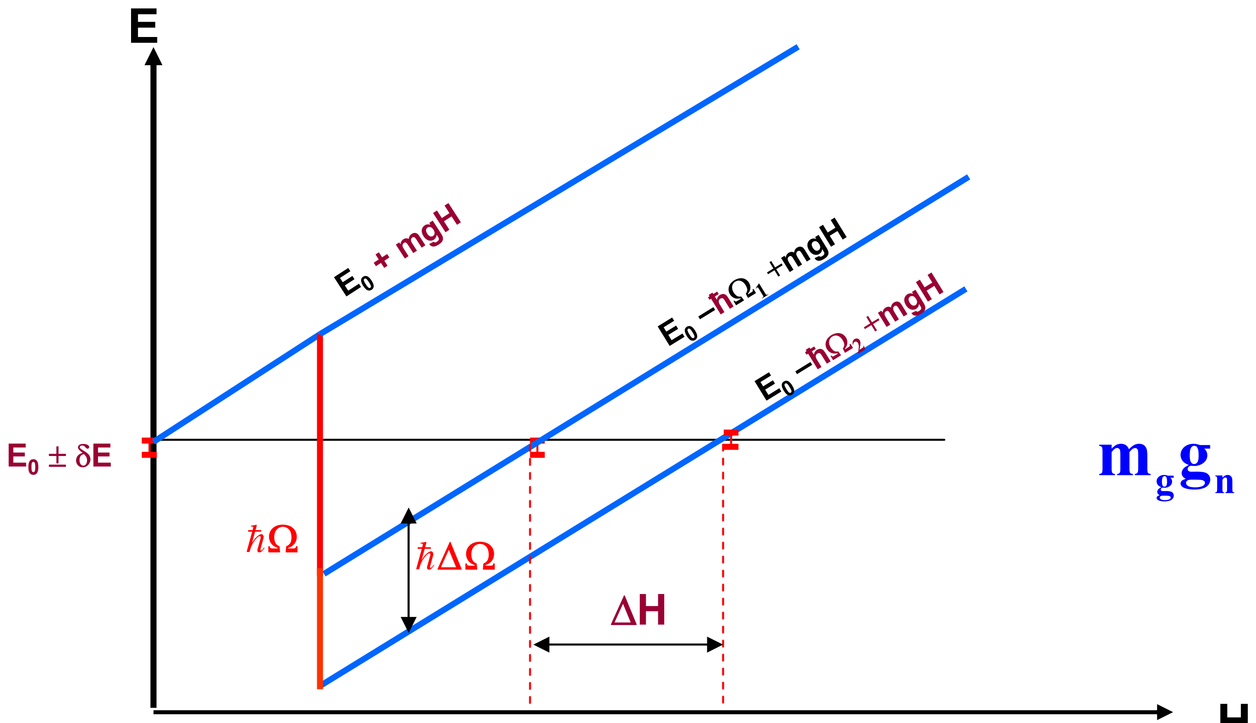
$$\frac{\Delta V_{exp}}{\Delta V_{th}} = 0.99 \pm 0.06_{stat} \pm 0.02_{syst}$$

$$a_{max} = A\Omega^2 = 72 m/s^2$$

A. I. Frank, P. Geltenbort, M. Jentschel, et al.. JETP Letters, 93 (2011) 361–365

- ***FP interferometers and other multilayers structures for UCN spectrometry***
- ***Gravity UCN spectrometer with FP interferometers***
- ***Moving grating as a nonstationary device***
- ***Neutron focusing in time***
- ***Accelerating medium effect***
- ***Test of the weak equivalence principle for neutron***

Idea of the experiment

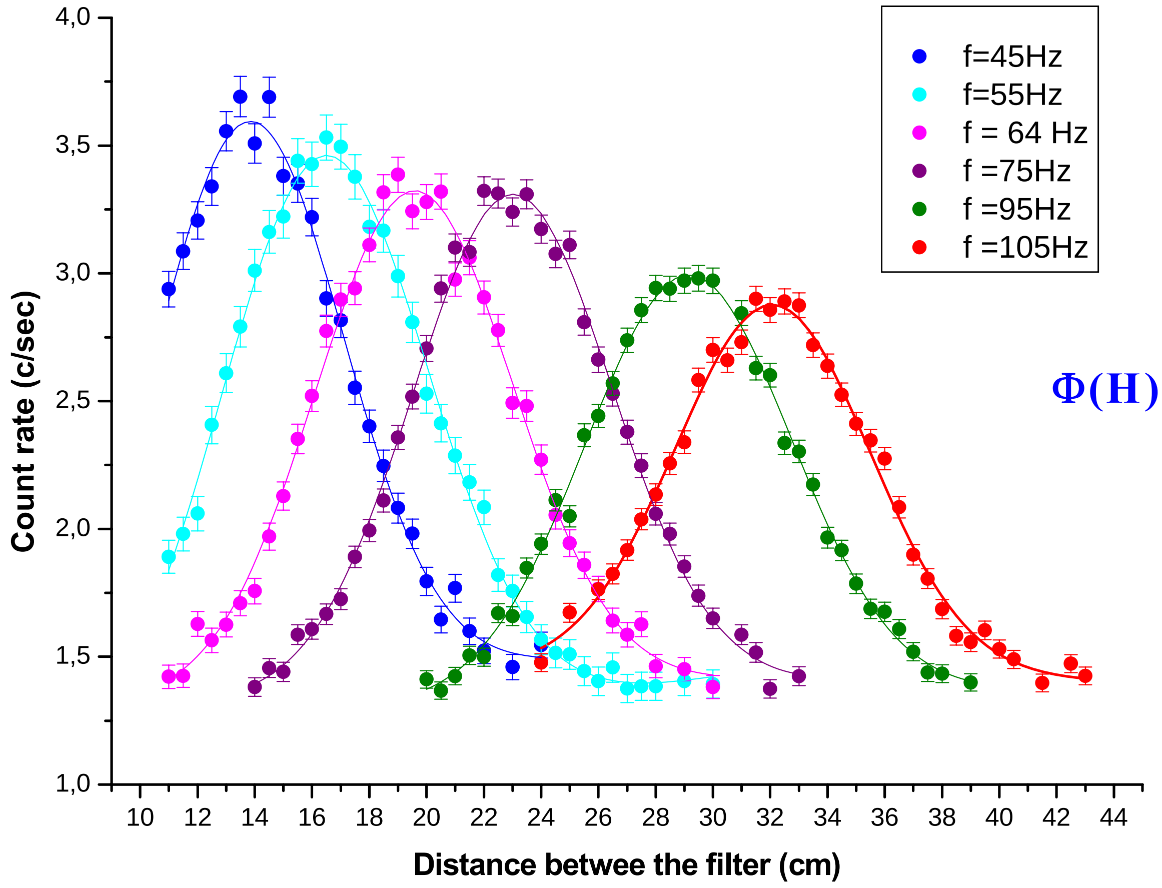


$$m_g g_n = \hbar \frac{\Delta\Omega}{\Delta H}$$

Two components are necessary for the realization

1. **Non stationary device**
2. **Spectrometric elements**

Experimental results

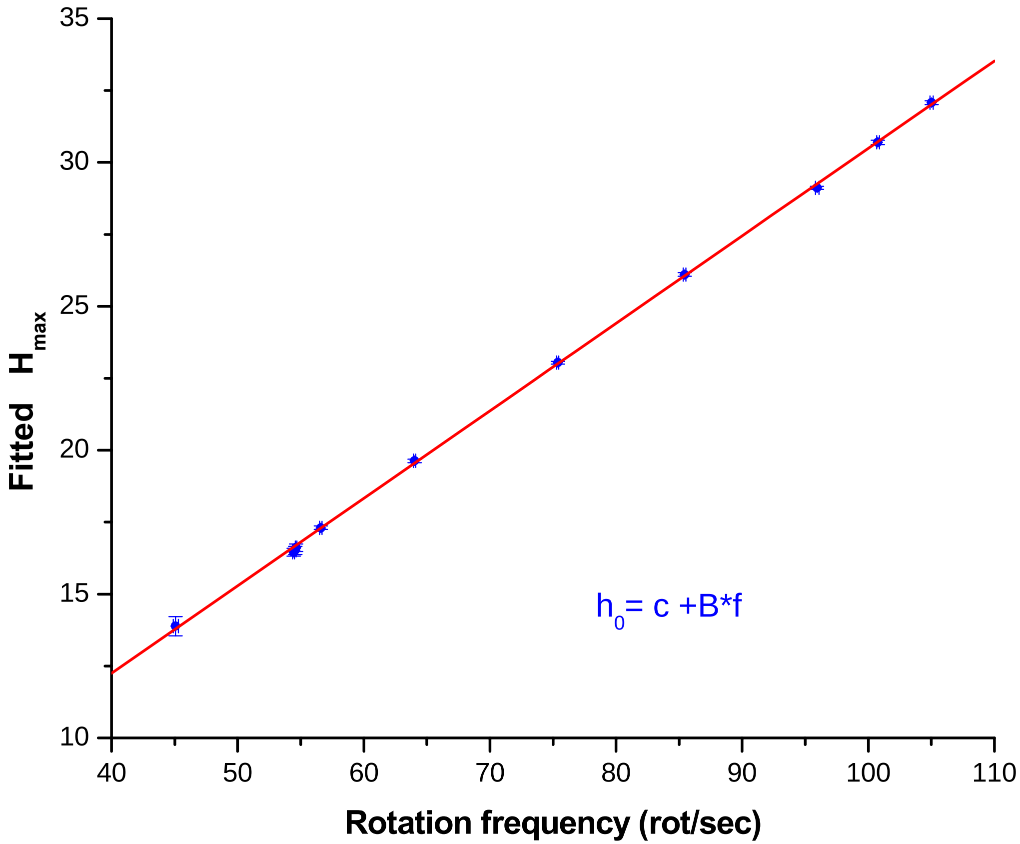


$$\Phi(H) = \int f(E) f(E + m_g a_n H - \hbar\Omega) dE$$

$$m_g a_n H_{max} = \hbar\Omega$$

Scanning curves measured at various grating rotation frequency and correspondent fitting curves

Final result



$B_{exp} = 0.3037 \pm 0.00065$

$$B_{th} = \frac{2\pi\hbar N}{m_i g}$$ N = 75398

$B_{th} = 0.30421$

$$1 - \frac{m_g g_n}{m_i g_{loc}} = (1.8 \pm 2.1) \cdot 10^{-3}$$

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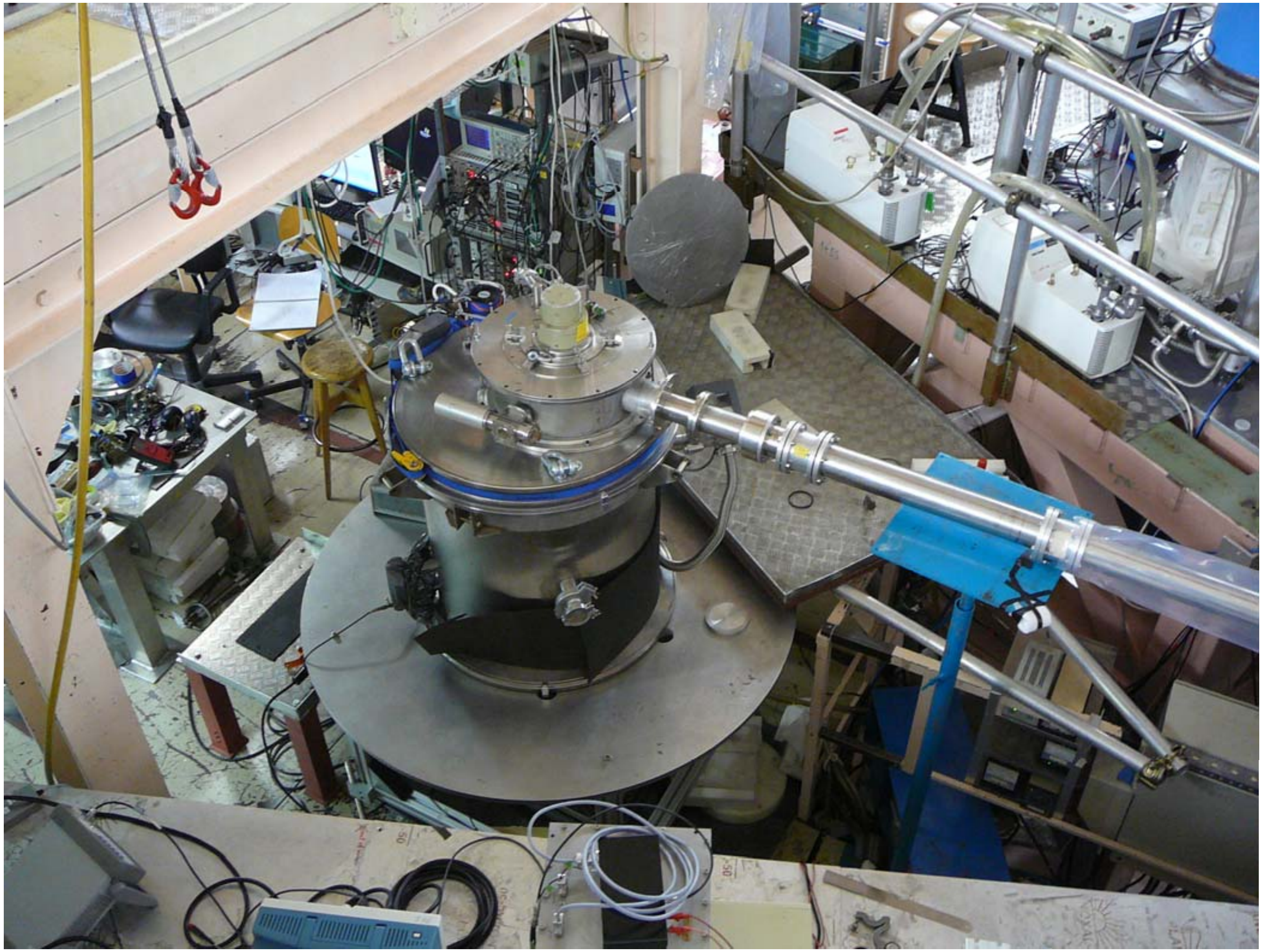
New spectrometer at the PF2 beam at ILL (2010).



New spectrometer at the PF2 beam at ILL
December 2011 – October 2012 (We hope)
Presentation of German Kulin (Friday, 25 May)

Authors

V.I.Bodnarchuk, I.V.Bondarenko, S.Gorunov,
D.A. Korneev, G.V.Kulin, D.V. Kustov,

A.Cimmino, A.G.Klein

S.N. Balashov, S.V.Masalovich,V.G. Nosov, A.N. Strepetov

P. Geltenbort, P. Høghøj, M. Jentschel

Thank you for your attention