Test of the equivalence principle with UCN

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Overview

1. Equivalence principle test for neutrons (short review)
2. Neutron quantum gravity experiment of a new type
3. Possibility of the increasing of its accuracy.

Test body	Attractor (distance)	Result	Reference
Al и Au (30g)	Sun	$\eta(\mathbf{Au},\mathbf{Al}) = (1.3 \pm 1.0)\times 10^{-11}$	1
Al и Cu (350g)	Galileo Type experiment (Earth)	$\Delta g/g = (2.9 \pm 7.2)\times 10^{-10}$	2
Be и Ti (5 g)	Earth	$\eta_{\mathbf{Earth,Be-Ti}} = (0.3 \pm 1.8)\times 10^{-13}$	3
Atoms $^{85}Rb/^{87}Rb$	Earth	$\Delta g/g = (1.2 \pm 1.7)\times 10^{-7}$	4
(Lunar laser ranging)	Sun	$\left\|(M_g/M_i)_{\mathbf{Earth}} - (M_g/M_i)_{\mathbf{Moon}}\right\| = (-1.0 \pm 1.4)\times 10^{-13}$	5
Cu and Pb (10g)	Attractor ^{238}U, (2.6T) 20cm	$\frac{\Delta \mathbf{a}_{(Cu-Pb)} = (1.0 \pm 2.8)\times 10^{-13}\,\mathbf{cm/s^2}}{\mathbf{a} = 9.8\times 10^{-5}\,\mathbf{cm/s^2}}$	6

$$\eta(\mathbf{A},\mathbf{B}) = \frac{\Delta \mathbf{a}}{\mathbf{a}} = 2\frac{(M_g/m_i)_A - (M_g/m_i)_B}{\left[(M_g/m_i)_A + (M_g/m_i)_B\right]}$$

1. P.G. Roll, R. Krotkov, and R.H. Dicke, Ann. Phys. (N.Y.) 26, 442 (1964)
2. S.Carusotto, V.Cavassinni, A.Mordacci et. al. Phys.Rev Lett. **69**, 1722 (1992)
3. S. Schlamminger, K.-Y. Choi, T. A. Wagner, et al. Phys.Rev Lett 100, 041101 (2008)
4. S. Fray, C. A. Diez, T. W. Hänsch, and M. Weitz. arXiv:physics/0411052 v.2 (2005)
5. J. G. Williams, S.G. Turyshev, and D. H. Boggs, Int.J.Mod.Phys.**D18**:1129-1175, (2009)
6. G. L. Smith, C. D. Hoyle, J. H. Gundlach, E. G. Adelberger, B. R. Heckel, and H. E. Swanson. Phys. Rev. Rev. **D 61**, (1999) 022001

Equivalence principle tests with neutrons (Short review)

1. **Gravitational Acceleration of Neutrons***

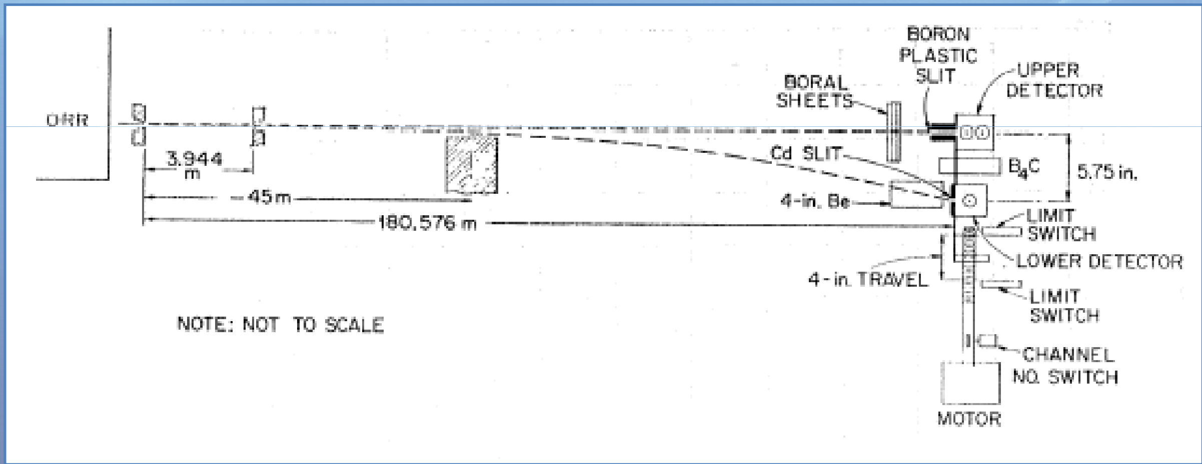
A. W. McReynolds

Brookhaven National Laboratory, Upton, New York

(Received May 11, 1951)

$g = 935 \pm 70 cm/sec^2$

2. J.W.Dabbs,J.A.Harvey, D.Pava and H.Horstmann, 1965



$g(002) = 973.1 \pm 7.4 cm/sec^2$

$g(100) = 975.1 \pm 3.1 cm/sec^2$

$g_{loc} = 979.74 cm/sec^2$

L.Koester, 1976

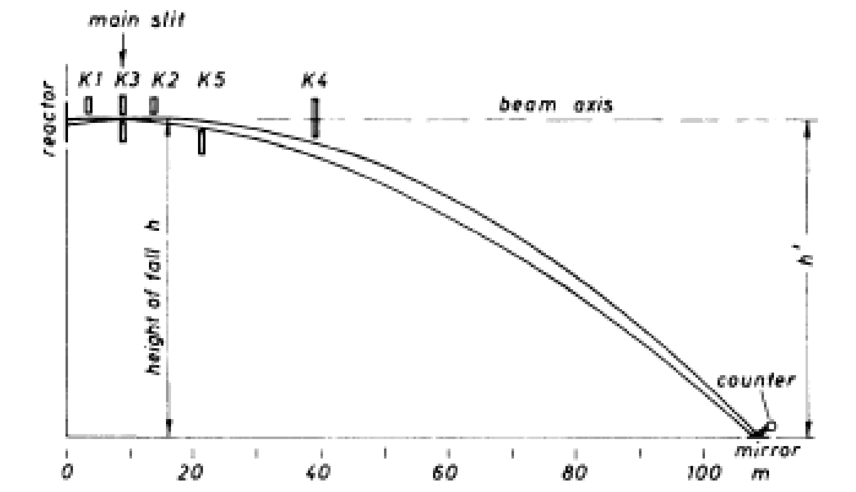


FIG. 1. Principle of the neutron gravity refractometer. $K1, \dots, K5$: slits and stopper for the neutron beam

$$mgh_0 \text{ € } U_{eff} = \frac{2\pi h^2}{m}\rho b$$

Knowing the neutron mass **m** and local free fall acceleration g_{loc} one can obtain the effective scattering length b_{eff}

$$b_{eff} = \frac{m^2 g_{loc} h_0}{2\pi\hbar^2\rho}$$

Coherence length **b** was measured also in the neutron scattering experiment with **Pb** and **Bi**. Thus the equivalence factor γ was found

$$m_g g_n h_0 = \frac{2\pi\hbar^2}{m_i}\rho b \qquad \gamma = \frac{b_{eff}}{b} = \frac{m^2}{m_i m_g}\frac{g_{loc}}{g_n}$$

$1-\gamma = (3\pm3)\times10^{-4}$ V.F.Sears,1982

J. Schmiedmayer, NIM A 284, (1989) 59 $\gamma = 1.00011 \pm 0.00017$

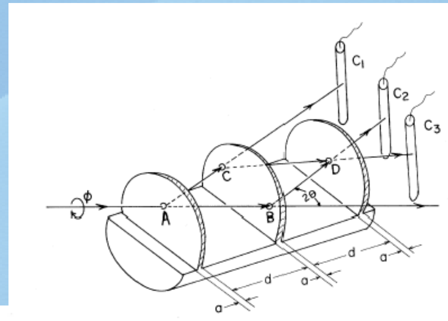
Koester's experiment and the problem of n-e scattering

When the value of b_{coh} extracts from the total cross section data it is necessary to take into account n-e scattering. For the case of **Pb** and **Bi** correspondent corrections are of the order **1%.** Consequently, if one aim to reach 10^{-4} in precision of b_{coh} the amplitude of n-e scattering must be known with precision of **1%**.

It is not evident that b_{ne} is known with such precision even now

Quantum experiments with neutron interferometer

R.Colella, A,W.Overhauser and S.A. Werner (COW), 1975



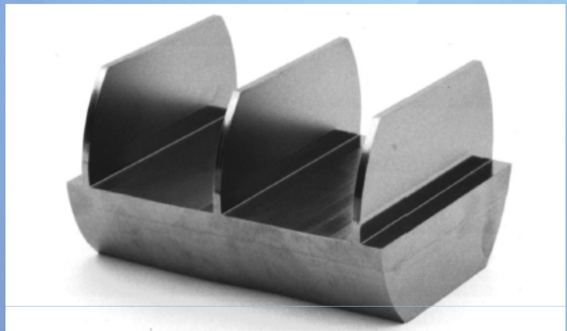


FIG. 5. A photograph of the symmetric interferometer used in this experiment. The blades of the interferometer are 3.077 mm thick and 50.404 mm apart. This interferometer was machined at Atominstitut, Vienna, Austria.

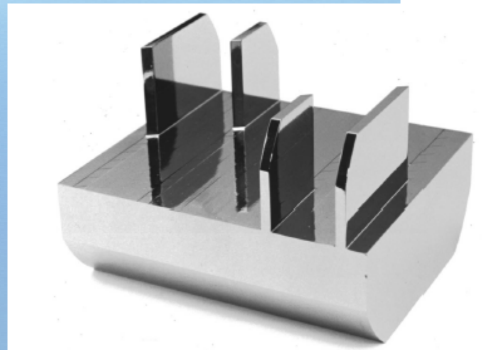


FIG. 4. A photograph of the skew-symmetric interferometer used in this experiment. The dimensions of the interferometer are $d_1=16.172$ mm, $d_2=49.449$ mm, and $a=2.621$ mm. This interferometer was machined in the physics shop at the University of Missouri-Columbia.

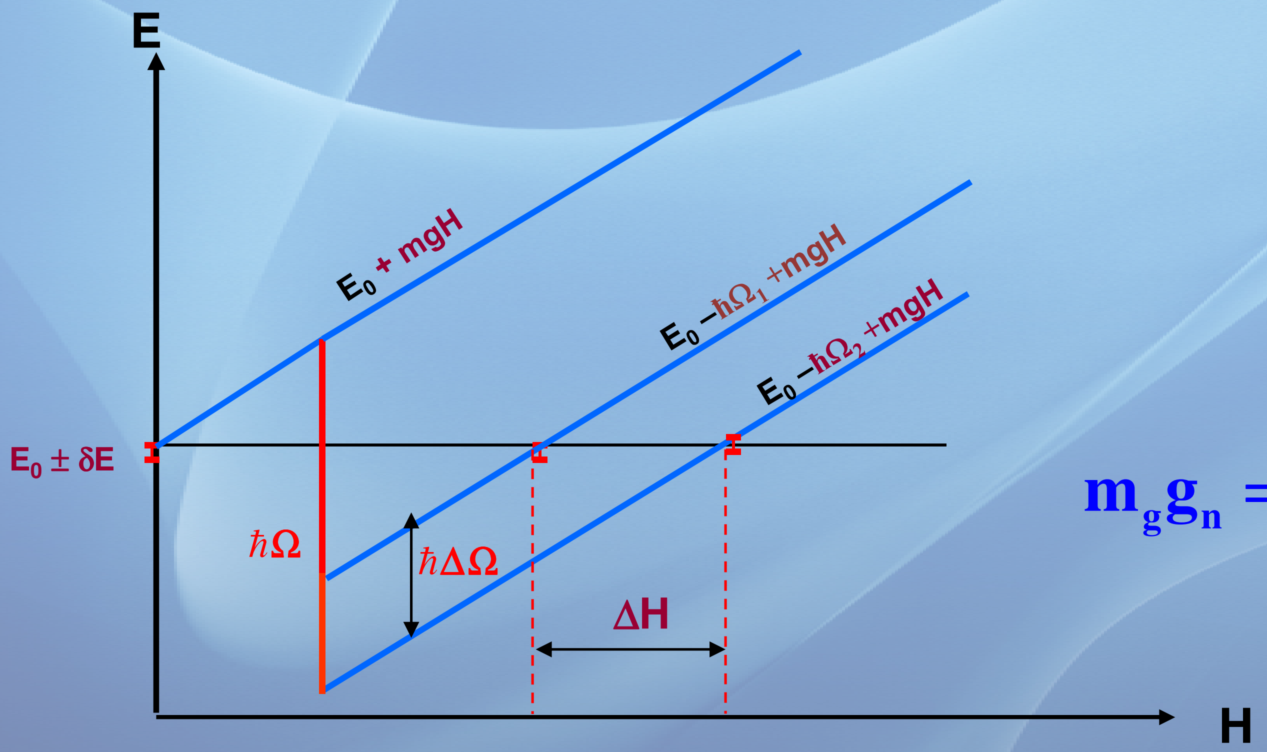
The experimentally obtained values for the gravitationally induced phase factor *u* were lower than the theoretically expected value by 1.5% for the skew-symmetric interferometer data and 0.8% for the symmetric interferometer data in measurements with relative uncertainties of 0.12% and 0.11%, respectively.

K.S.Litrell, B.E.Allman and S.A.Werner, 1997

ILL experiment of G.van der Zouw, et al. (2000) with the accuracy of about 0.9% did not solve the problem.

Experiment with UCNs (2006)

Idea of the experiment



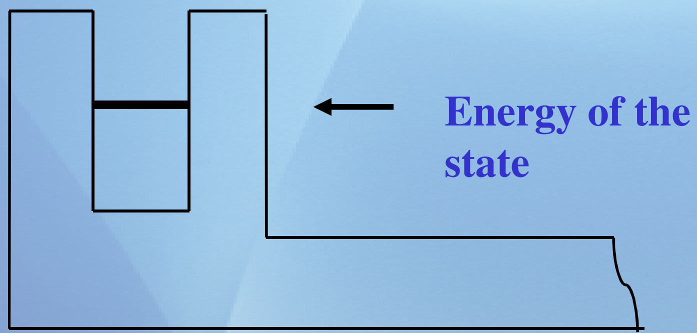
$$m_g g_n = \hbar \frac{\Delta\Omega}{\Delta H}$$

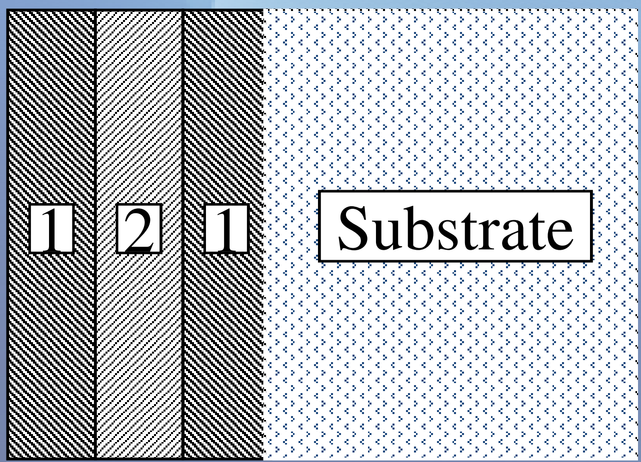
Two components are necessary for the realization

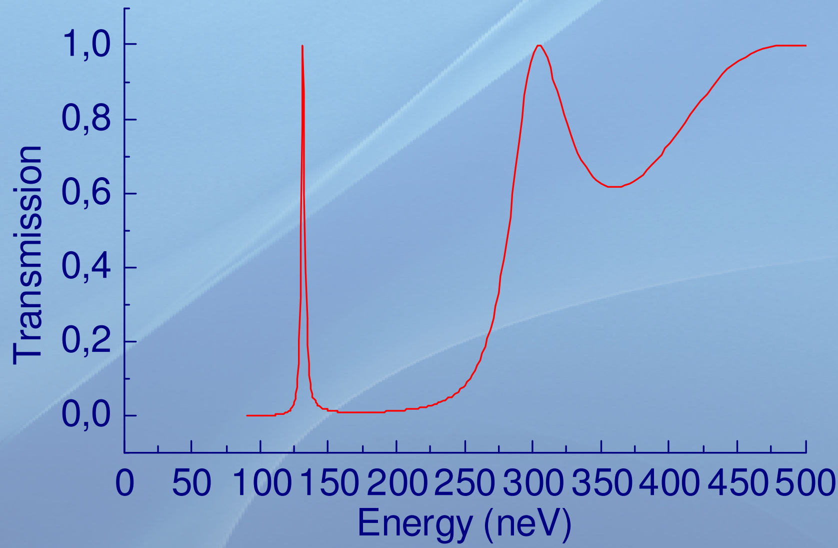
1. Spectrometric elements
2. Non stationary device

The spectrometry of UCN based on the using of quantum monochromator – Fabry-Perot interferometer

Fabry Perot interferometer
(Neutron Interference filter)

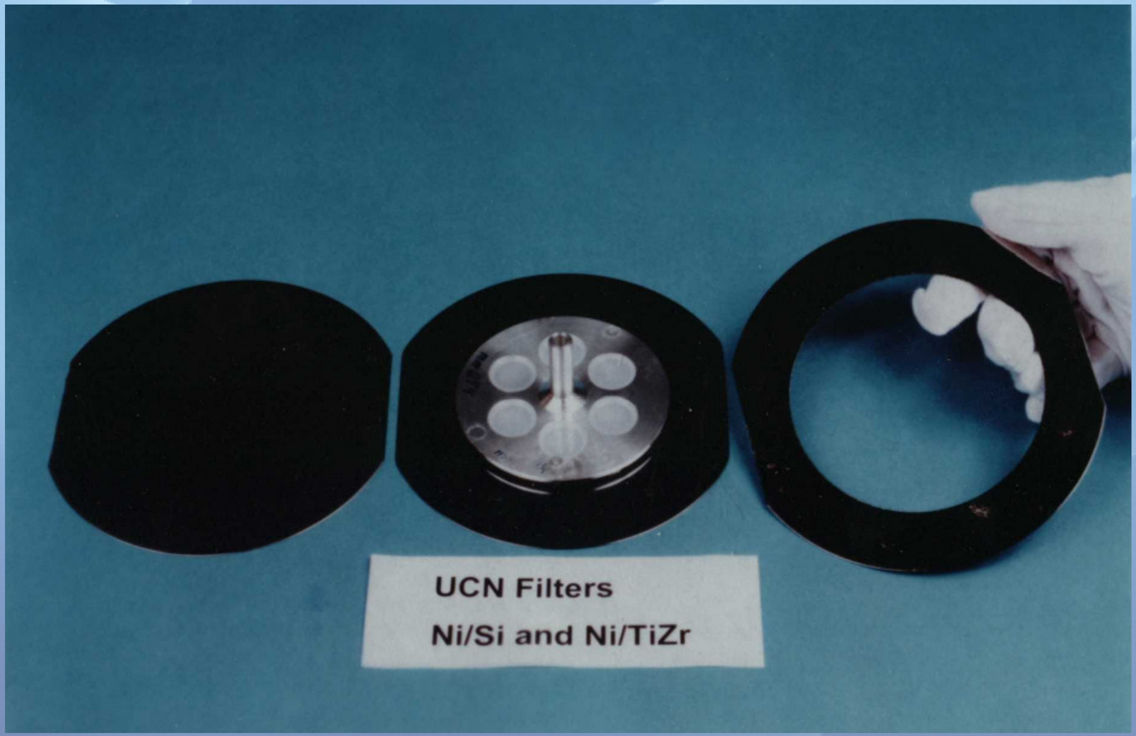






$$U_{1,2} = \frac{2\pi\hbar^2}{m}(\rho b)_{1,2}$$

Interference filters – neutron Fabry –Perot interferometers

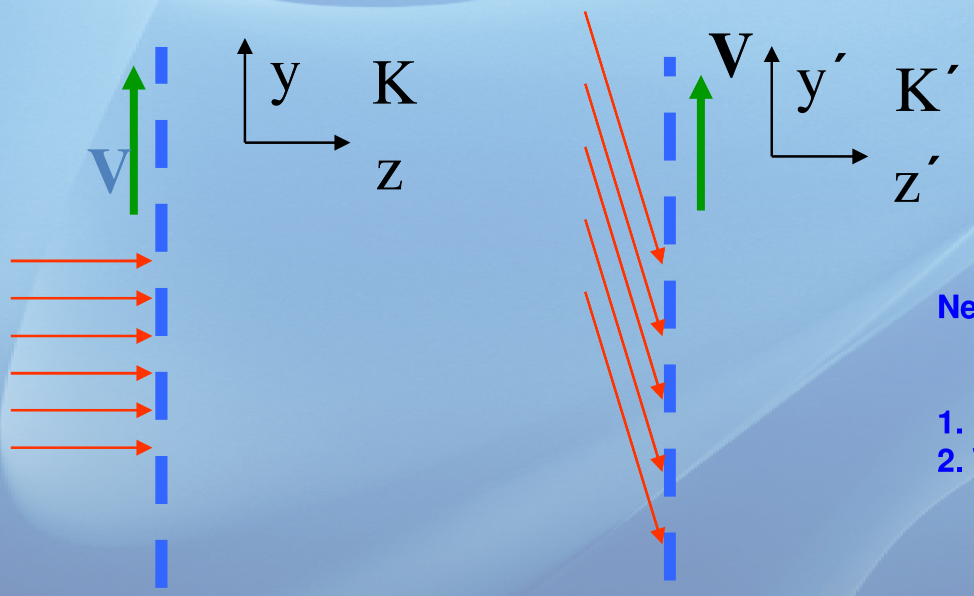


Multilayer structures on a Si wafer.
Number of layers 5-120. Typical thickness of a layer 200-300 Å. Uniformity 2-3%

Moving grating as a non stationary device

Moving grating

A.Frank, V.Nosov, 1994



Neutron diffraction by surface waves:

1. I.M.Frank, 1975.
2. W.A. Hamilton., et al (1987)

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

2. Galilean transformation of the wave function.

Main theoretical results

$$\Psi(z,y,t) = \sum_n a_n \exp[i(k_n z + q_n y - \omega_n t)]$$

$$L^{-1} << k$$

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

$$\Omega = \frac{2\pi}{T} = 2\pi f = 2\pi\frac{V}{L} \qquad q_n = n\cdot\left(2\pi/L\right) = nq_0$$

$$a_n = \frac{1}{L}\int_0^L \theta(y)e^{-iq_n y}dy$$

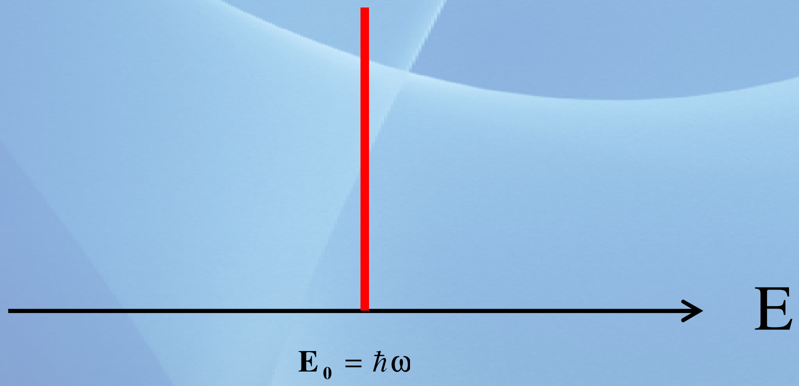
L – period of grating

$\theta(y)$ – (complex) transmission function for the single grating element

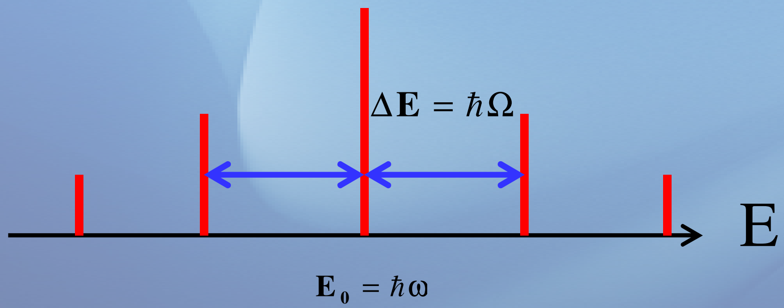
Moving grating as a quantum modulator

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

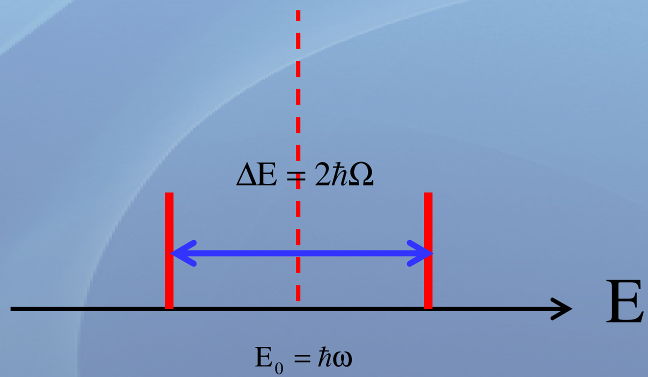
$$a_n = \frac{2}{i\pi n}, \qquad n = 2s - 1$$



Only odd diffraction orders

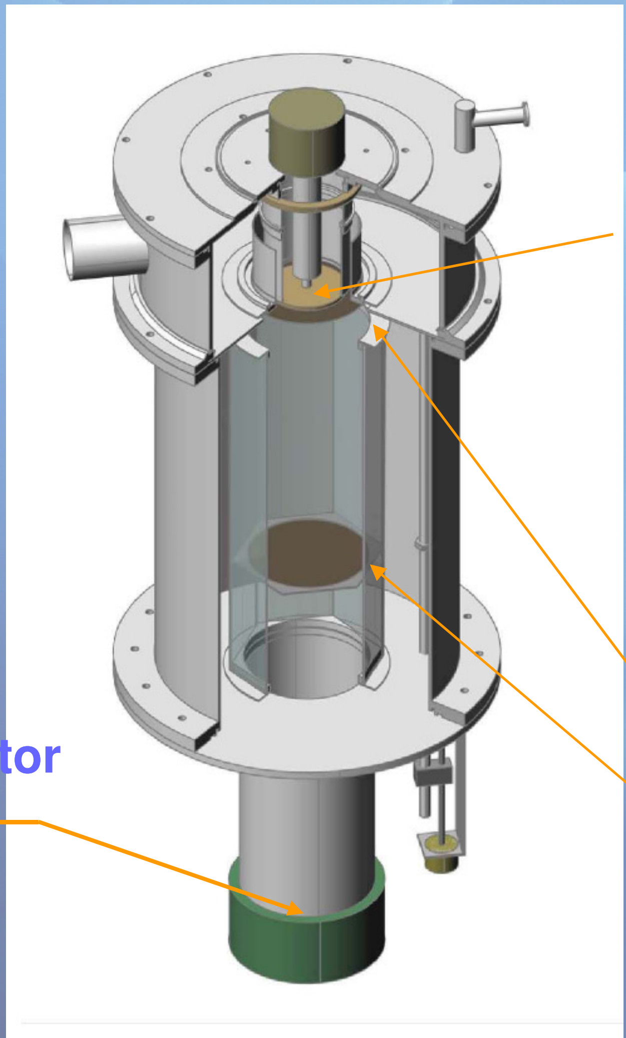


$a_0 = 0$! $\quad |a_{\pm 1}|^2 = \frac{4}{\pi^2} = 0.405$

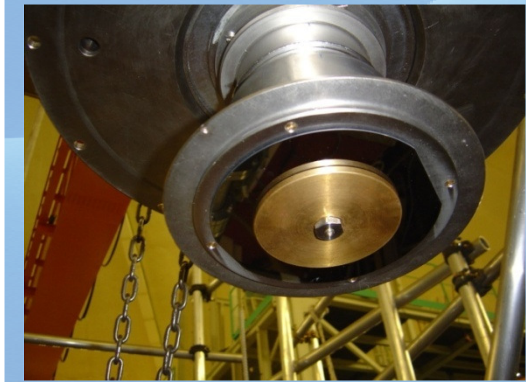


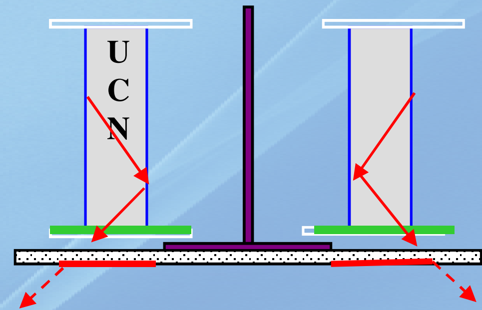
Diffraction in -1 order $(\Delta E = -\hbar\Omega)$ **was used in our experiment**

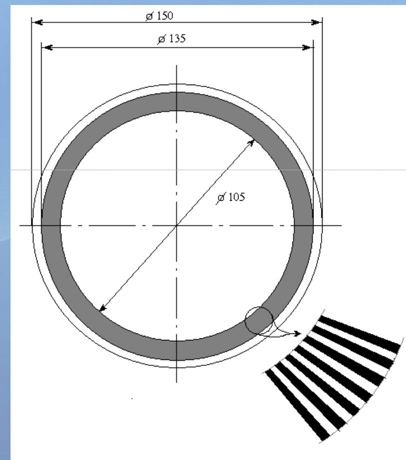
UCN spectrometer with Fabry-Perot interferometers



Detector





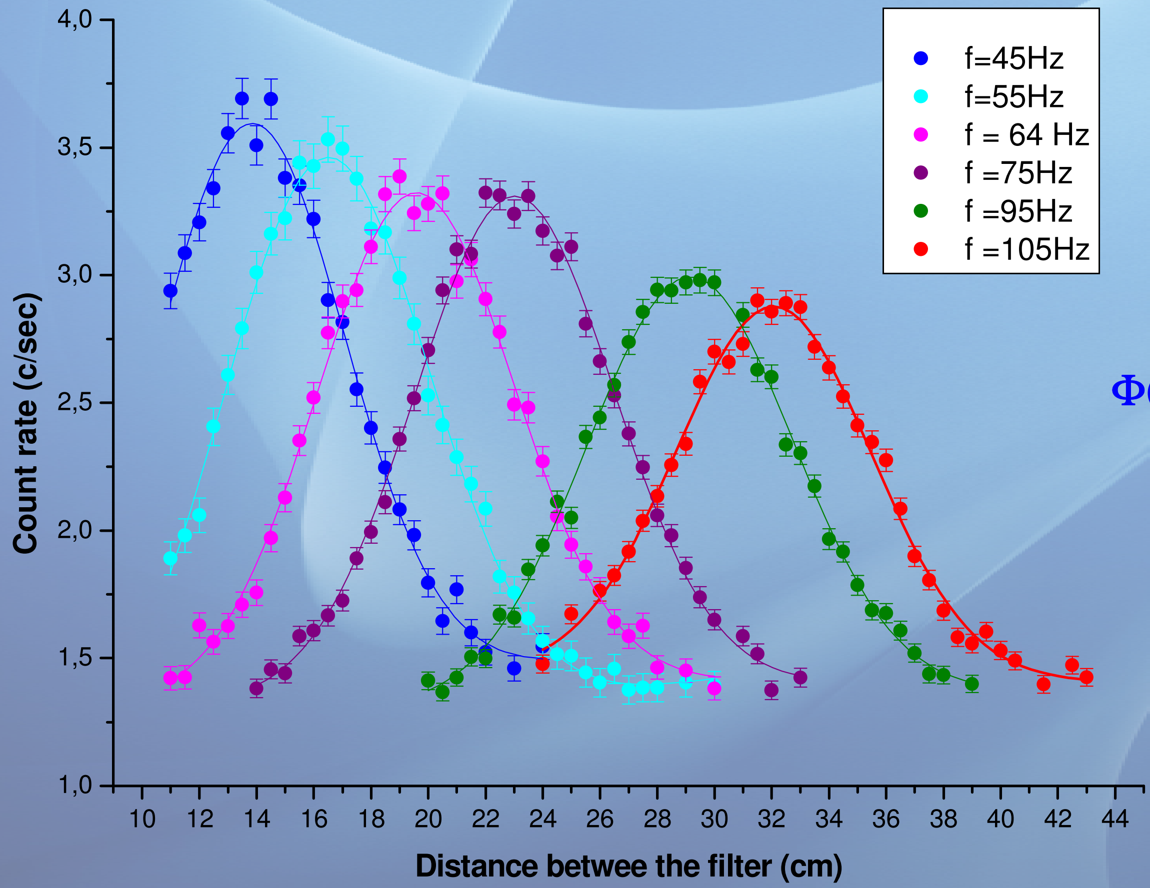


$$\Omega = 2\pi \frac{2\pi f R}{\alpha R} = 2\pi f N$$

where α is an angular period
N – number of groves

Two FPIs with variable distance between them

Experimental results

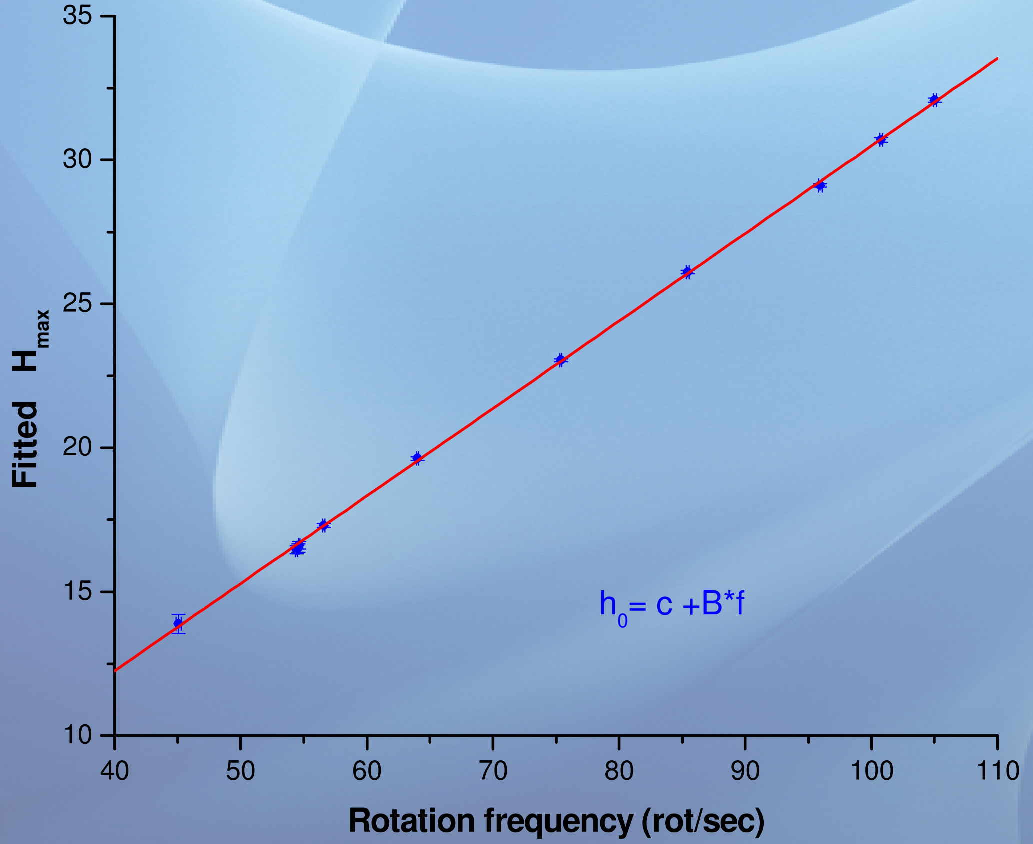


$$\Phi(H) = \int f(E) f(E + m_g a_n H - \hbar\Omega) dE$$

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

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

Final result



$B_{exp} = 0.3037 \pm 0.00065$

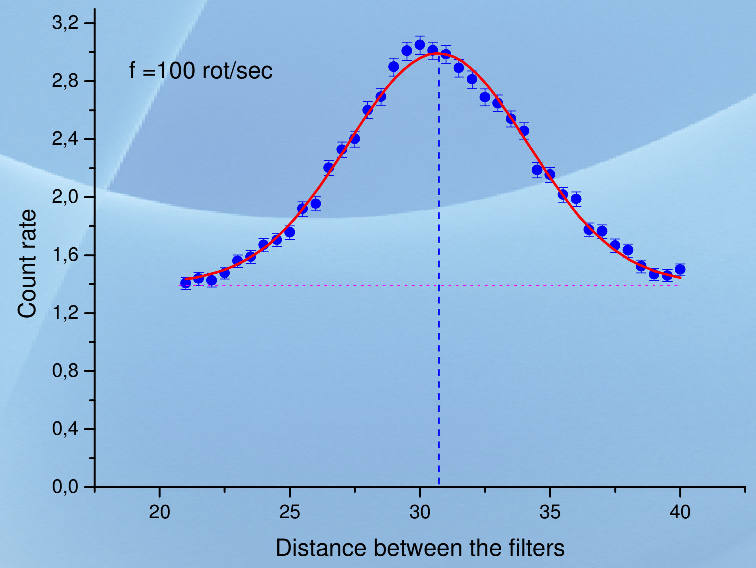
$$B_{th} = \left(\frac{\hbar}{m_i}\right)\frac{2\pi\hbar N}{g_{loc}}$$

N = 75398

$B_{th} = 0.30421$

$$1 - \frac{m_g a_n}{m_i g} = (1.8 \pm 2.1) \cdot 10^{-3}$$

Possibility of increasing accuracy of UCN experiment



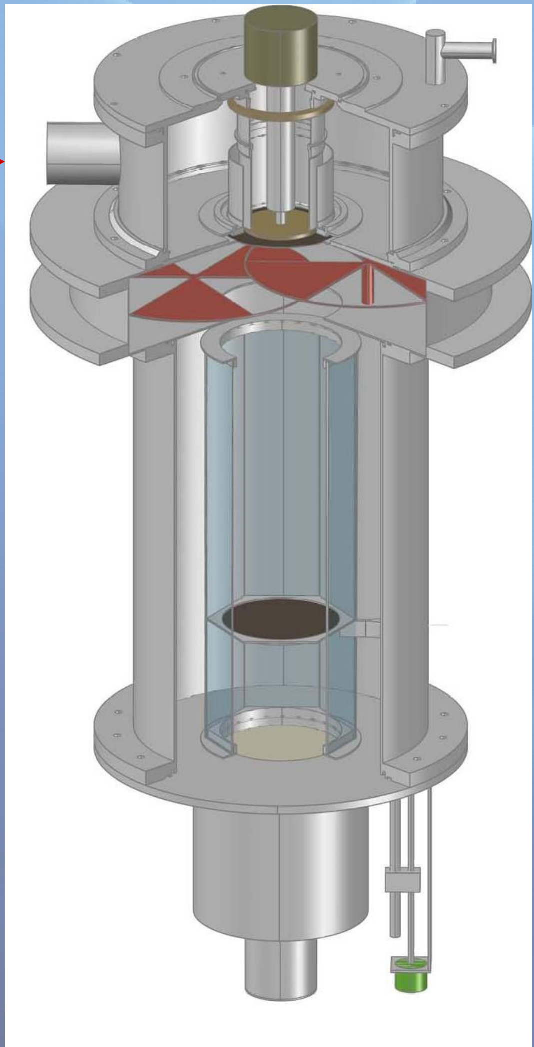
The main problems are:

1. Serial (point after point) method of the scanning curve measurements

2. Large influence of the background on the value of the measured center of the scanning curve.

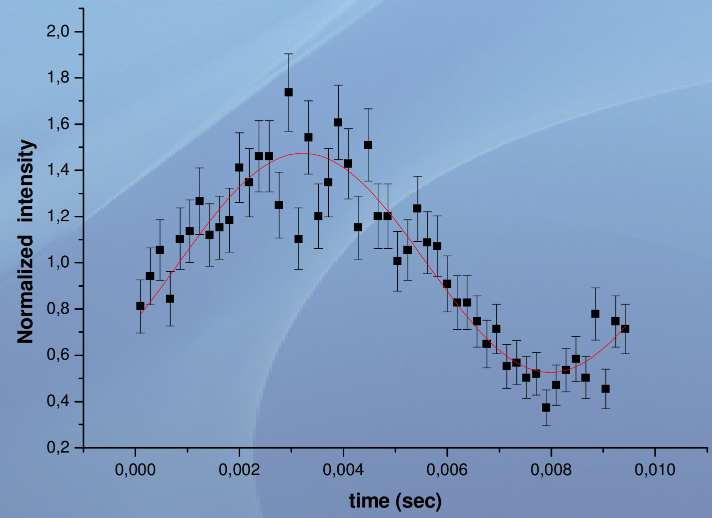
Nearest Future: New Gravity UCN spectrometer with FP-interferometers and modulation of intensity

UCN



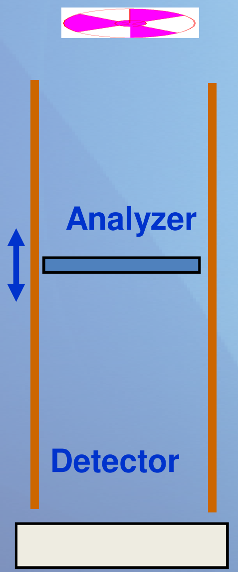
Alternative measurement method will be used.

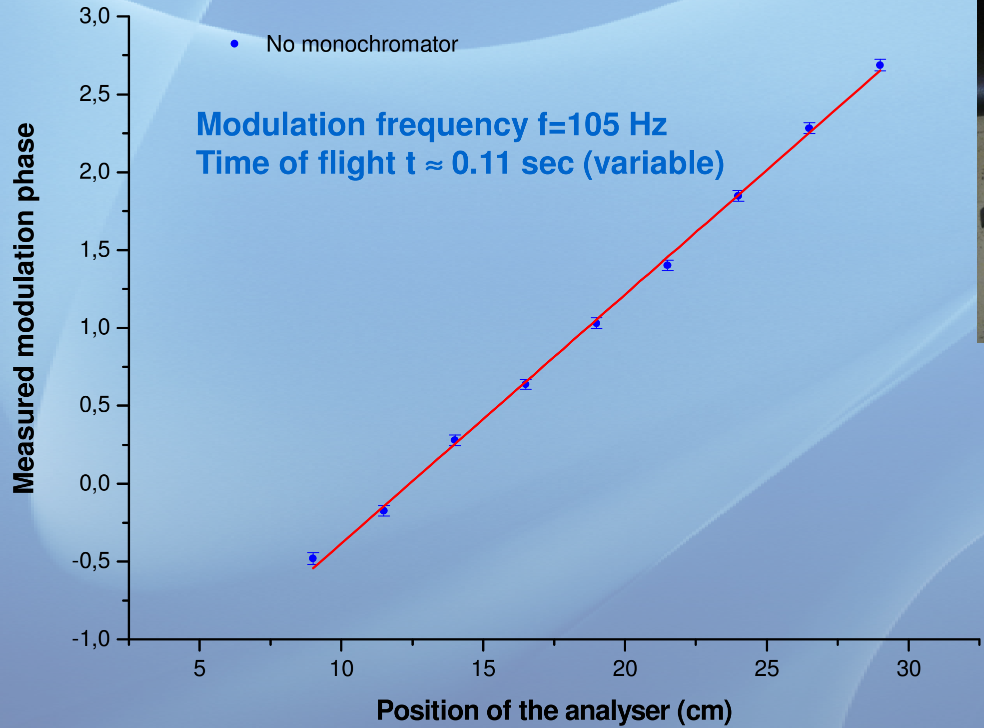
Time of flight with the measurement of the count rate modulation phase

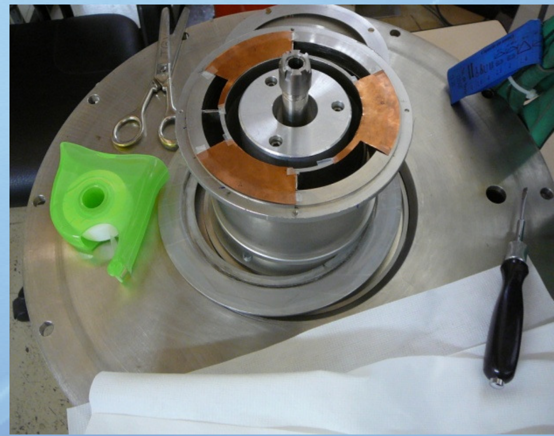


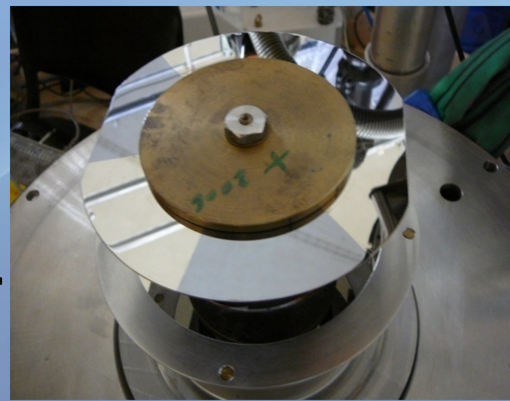
Count rate modulation measured in 2007. f = 105 Hz. t≈ 0.11 сек.

Time of flight spectroscopy by the measurement of the count rate modulation phase









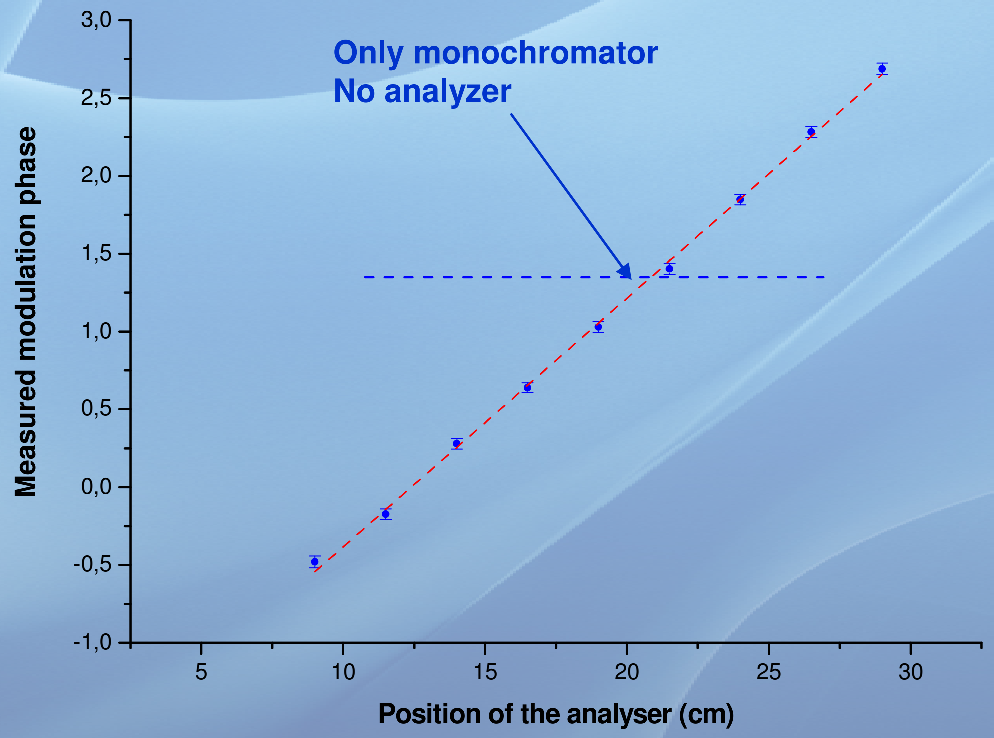
$\varphi(h) = 2\pi f t(h)$

$\varphi:\ 65$ radians

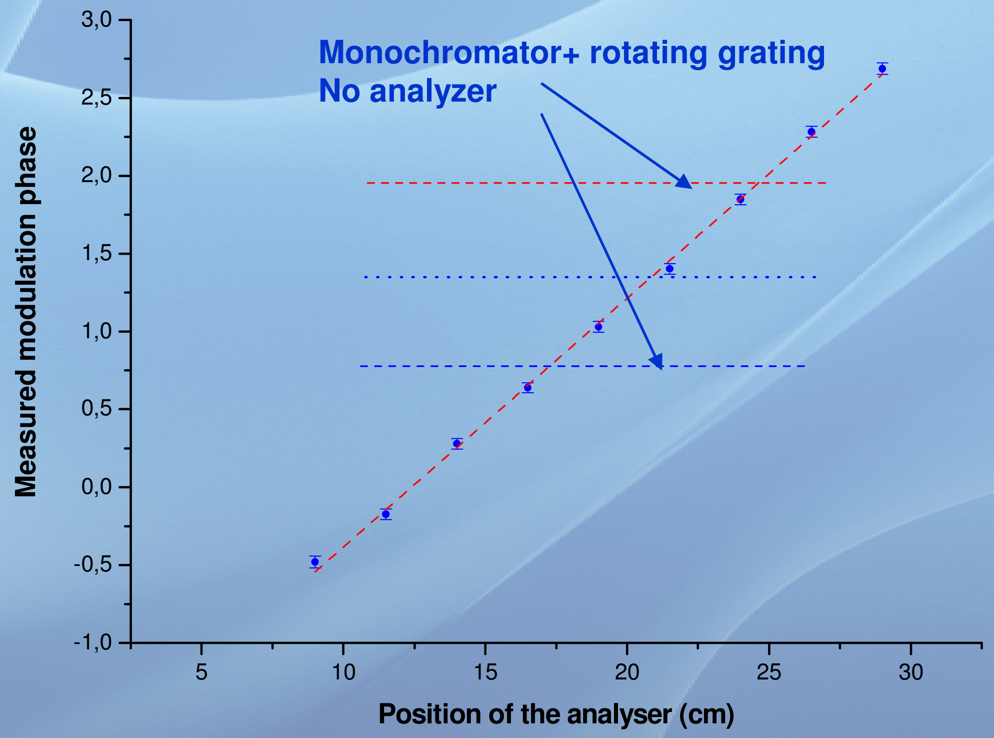
$$\frac{\Delta\varphi}{\varphi} = \frac{\Delta t}{t} = \frac{\Delta v}{v} = 4.5\times10^{-4}$$

1 hour of measurement per point

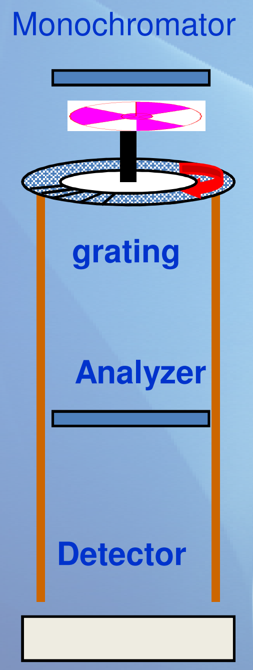
Time of flight spectroscopy by the measurement of the count rate modulation phase

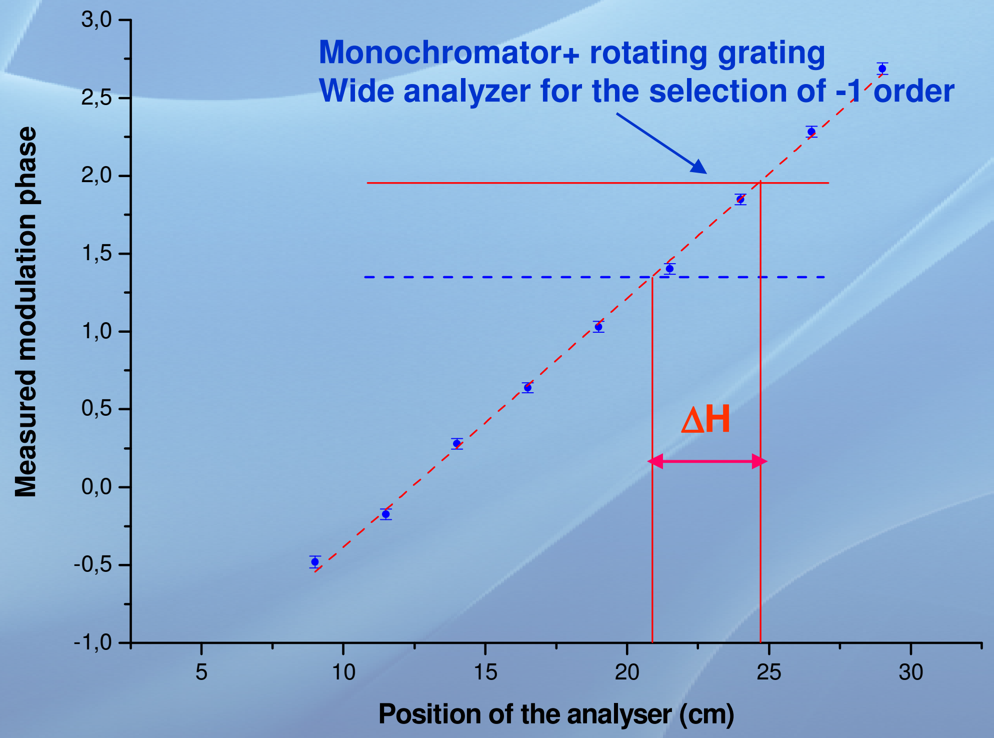


Time of flight spectroscopy by the measurement of the count rate modulation phase

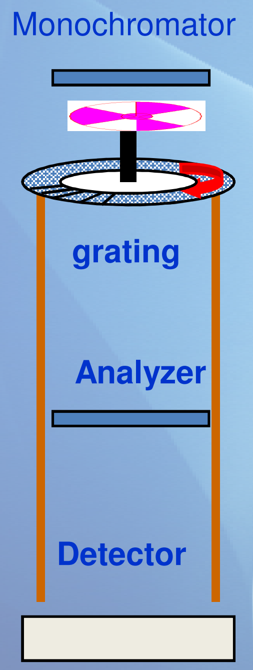


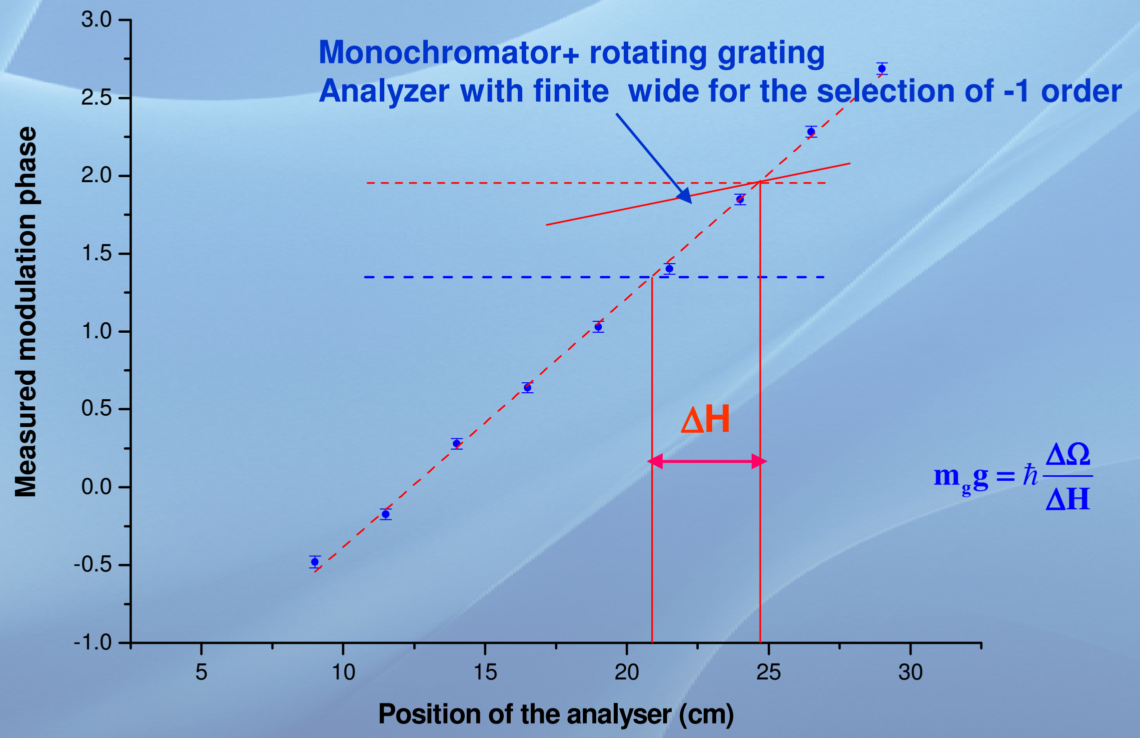
Time of flight spectroscopy by the measurement of the count rate modulation phase





Time of flight spectroscopy by the measurement of the count rate modulation phase



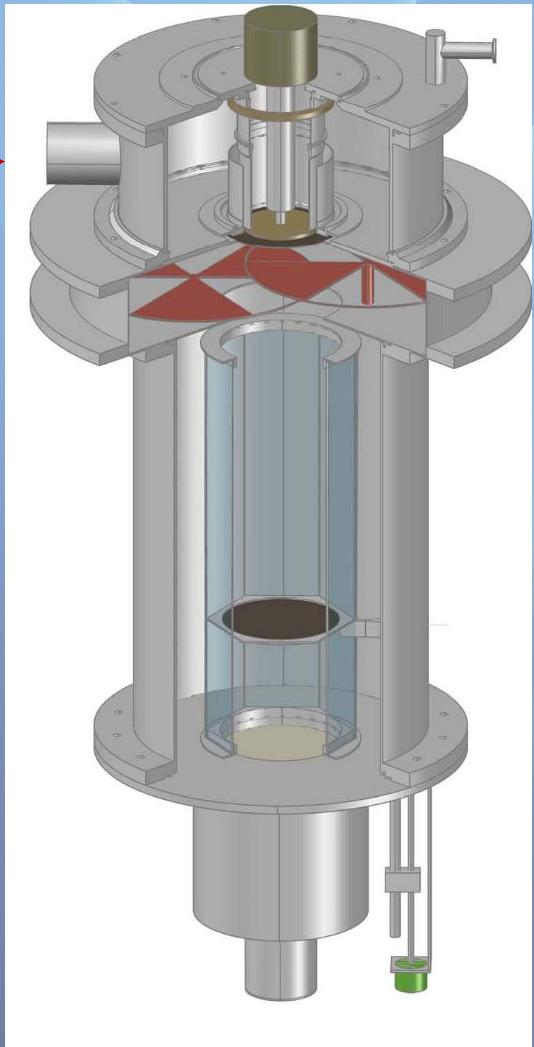


$$m_g g = \hbar \frac{\Delta\Omega}{\Delta H}$$

New experiment with UCN spectrometer using

FP-interferometers and modulation of intensity

UCN



Advantages:

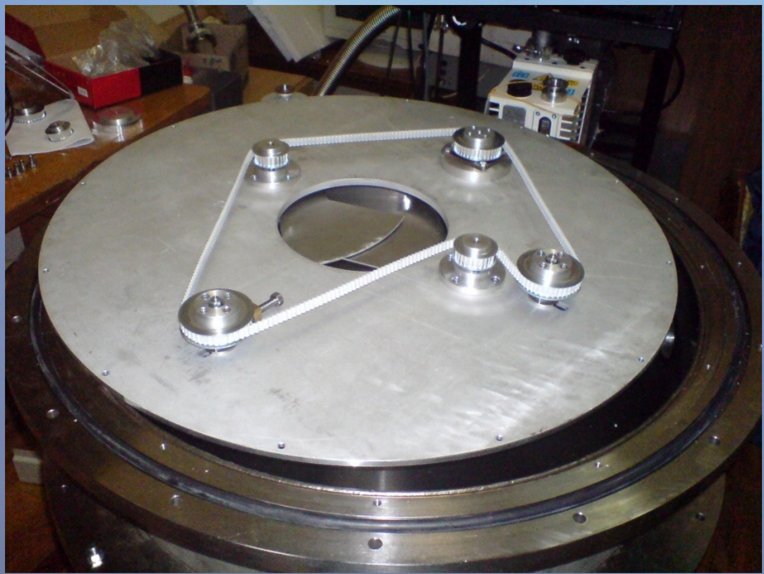
1. In contrast with calculated center of the scanning curve, the modulation phase did not sensitive to the background. (It may change only the amplitude of modulation).

2. It is not necessary to scan the full curve (40 points in 2006). Due to linear dependence of phase on filter position It is enough only to measure phase in some points.

Estimated sensitivity 2 $\times 10^{-4}$

(one cycle at PF2 ILL)

Step motor VSH 65HV and driver MCD + 93-70



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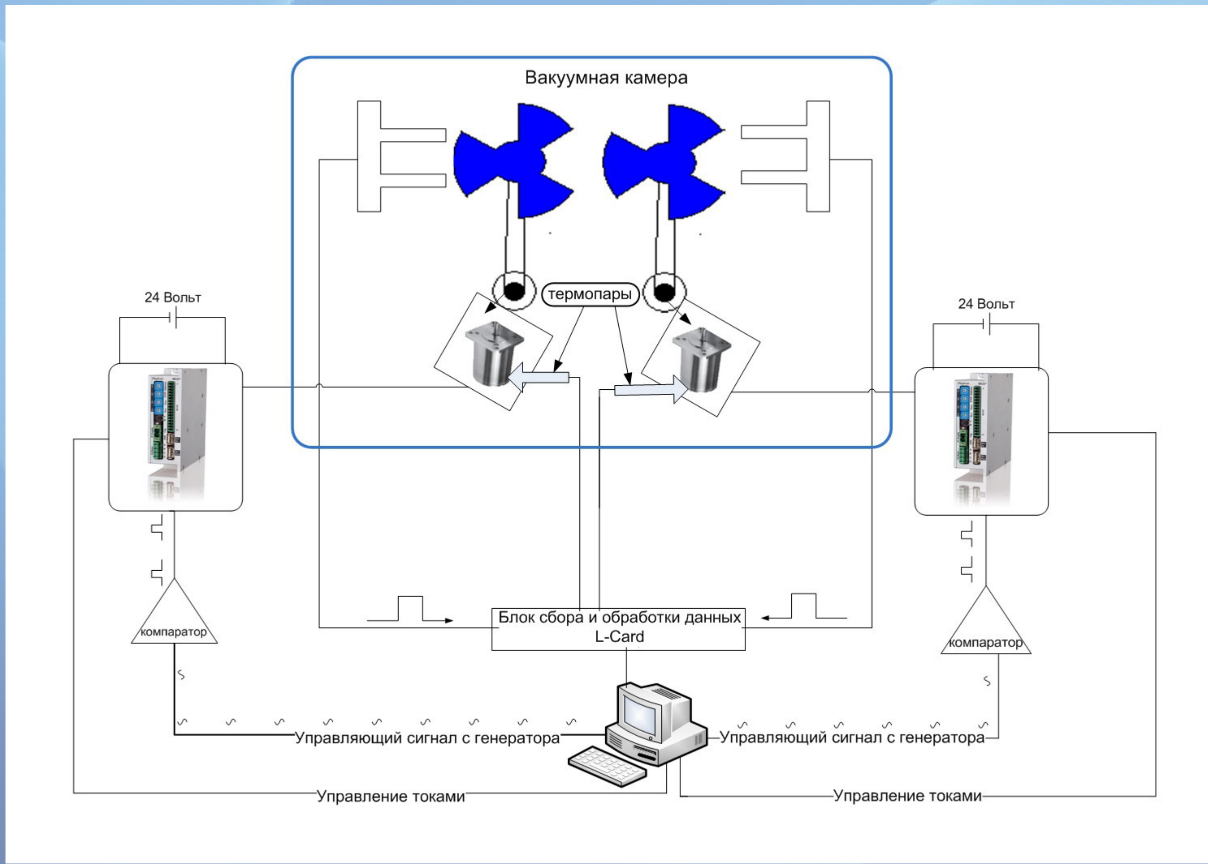
Thank you for your attention!


Вакуумная камера
термопары
24 Вольт
24 Вольт
Блок сбора и обработки данных
L-Card
компаратор
компаратор
Управляющий сигнал с генератора
Управляющий сигнал с генератора
Управление токами
Управление токами

Koester experiment. Modern view

1. The problem of n-e scattering.

When b_{coh} extracts from the measuring of the total cross-section, the n-e scattering must be taken into account. For the case of Pb and Bi this correction is about of 1%.
Thus for the accuracy of 10^{-4} the n-e scattering amplitude must be known with precision of 1%.

Experiment	Year	b_{ne}*10^{-3} *fm*
Melkonian, Bi cryst spectr σ_t [3] Re-estimation, Koester Re-estimation, Kopecky [4]	1959 1976 **1997**	-1.56±0.05 -1.49±0.05 -1.44±0.03±0.06
Krohn, aqngle distribution on gases Re-estimation, Krohn [5]	1966 **1973**	-1.34±0.03 -1.33±0.03
Alexandrov, ^{186}W [6]	1975	-1.60±0.05
Koester, filters $-b_{coh}$ Pb [7] Re-estimation, Nikolenko [8]	1976 **1990**	-1.364±0.025 -1.32±0.03
Koester, filters $-b_{coh}$ Pb [7] Re-estimation, Nikolenko [8]	1976 **1990**	-1.393±0.025 -1.33±0.03
Alexandrov, TOF σ_t - b_{coh} Bi [9] Re-estimation Nikolenko [8]	1986 1990	-1.55±0.11 -1.40±0.04
Koester, filters $-b_{coh}$ Pb, Bi [10]	**1986**	-1.32±0.04
Kopecky, liquid ^{208}Pb TOF σ_t [11]	**1995**	-1.31±0.03±0.4
Koester, ^{208}Pb,Bi TOF [12]	**1995**	-1.32±0.03
Kopecky, liquid ^{208}Pb TOF σ_t [4]	**1997**	-1.33±0.03±0.03
Kopecky, liquid Bi TOF σ_t [4]	**1997**	-1.44±0.03±0.04

It is not evident that b_{ne} is known now with such precision

Thanks to G. Samosvat