Two-wave acceleration effect and ultra-sensitive UCN spectrometry

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ISINN 31

Prehistory. Theoretical prediction of two new effects

Kazuo Tanaka

Reflection and transmission of electromagnetic waves by a linearly accelerated dielectric slab. Phys.Rev. A **25**, 385 , 1982

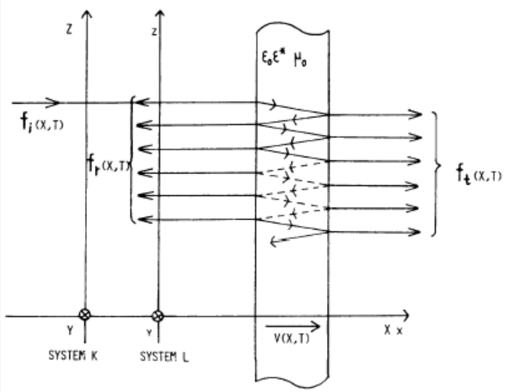


FIG. 1. Geometry of the problem.

$$\omega_p \cong \omega_0 + \frac{aL}{c^2}\omega_0\left[(2p-1)n-1\right]$$

$$\boxed{\Delta\omega \cong \frac{wd}{c^2}\omega_0(n-1)} \qquad (p=1)$$

To our knowledge, the Tanaka effect has not yet been observed.

F.W. Kowalsky

Interaction f neutrons with accelerating matter: test of the equivalence principle. Phys. Lett. A **25**, 335 , 1992

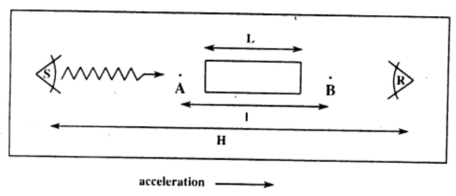


Fig. 1. The source, S, emits a neutron which propagates through the slab of material to the receiver, R. The slab, S, and R all accelerate rigidly with constant acceleration g in the direction shown. Points A and B are fixed in the inertial frame discussed in the text.

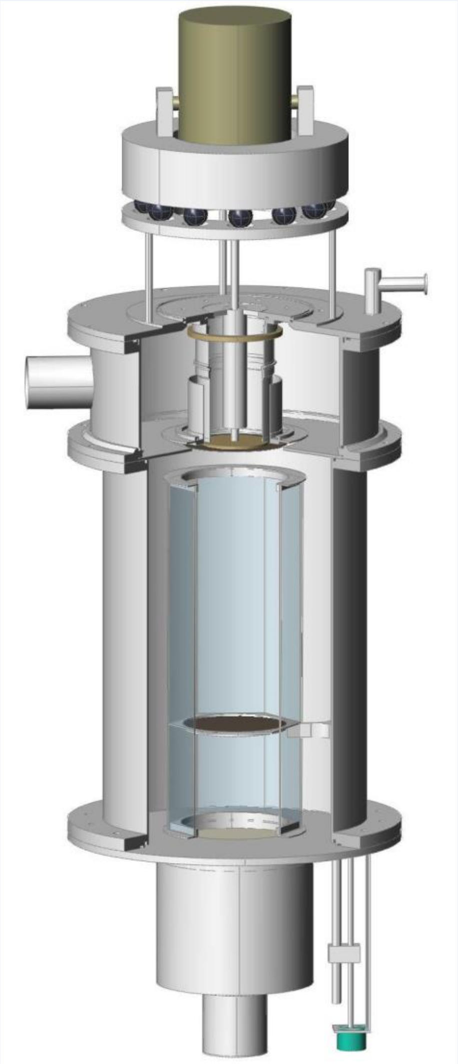
He founded a contradiction with the equivalence principle when calculated the problem but the effect of energy changes was predicted

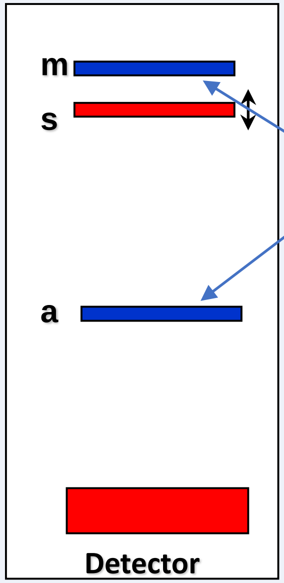
$$\boxed{\Delta E \cong mwd\left(\frac{1}{n}-1\right)}$$

The result was confirmed by alternative approaches by V.G.Nosov and A.I.Frank In 1998

Effect was discovered in 2007-2008 by the JINR – ILL Group

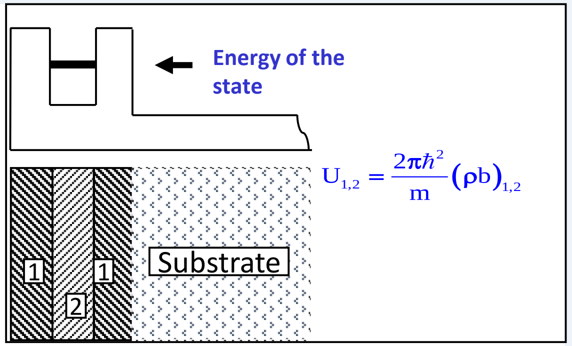
Precise UCN spectrometry

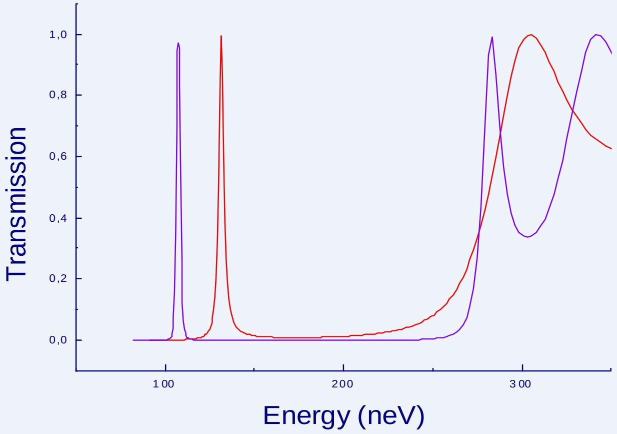


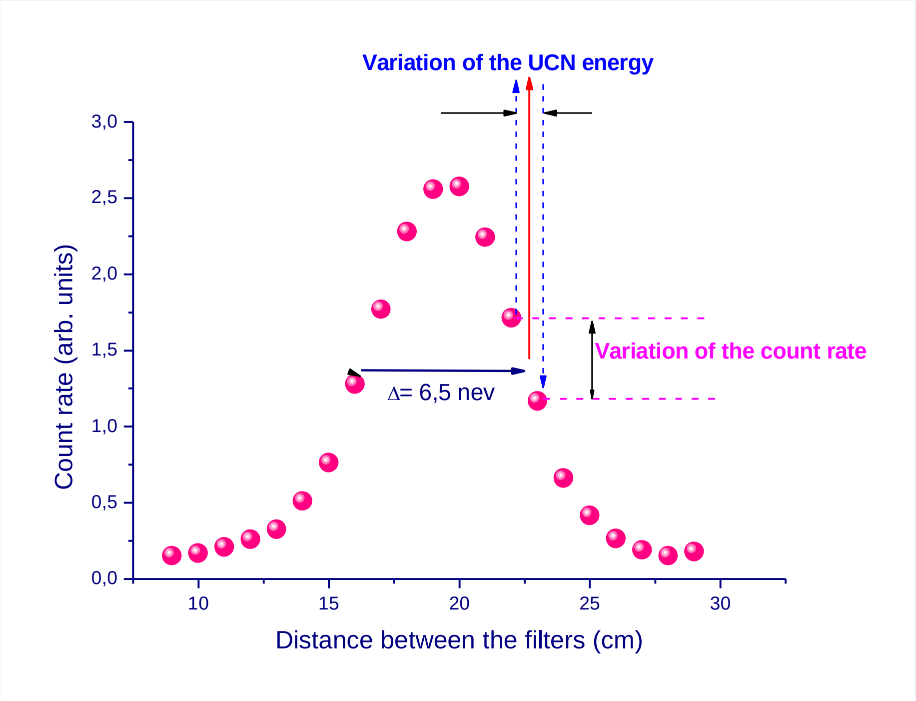


$$w \cong -A\Omega^2 \sin\Omega t$$

mg=1.02 neV/cm

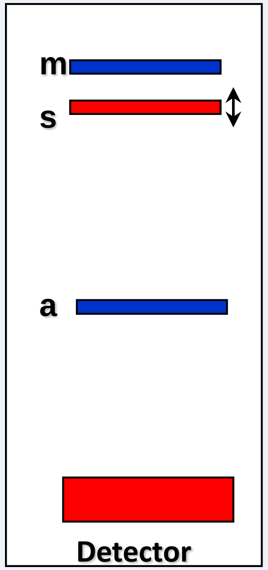


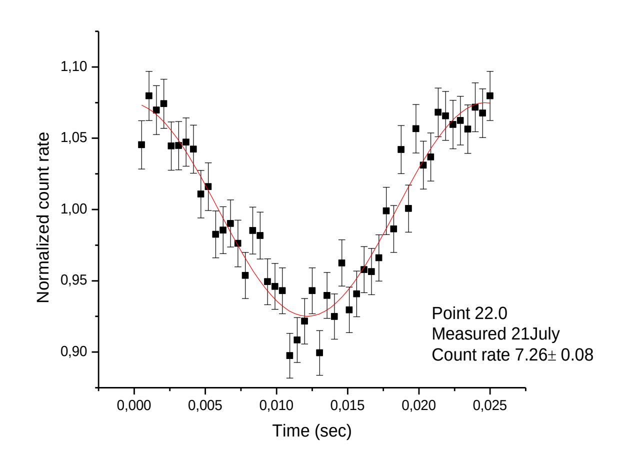




The periodic variation of the neutron energy, caused by the sample acceleration, leads to the periodical oscillation of the count rate

First observation of the effect of acceleration in neutron optics

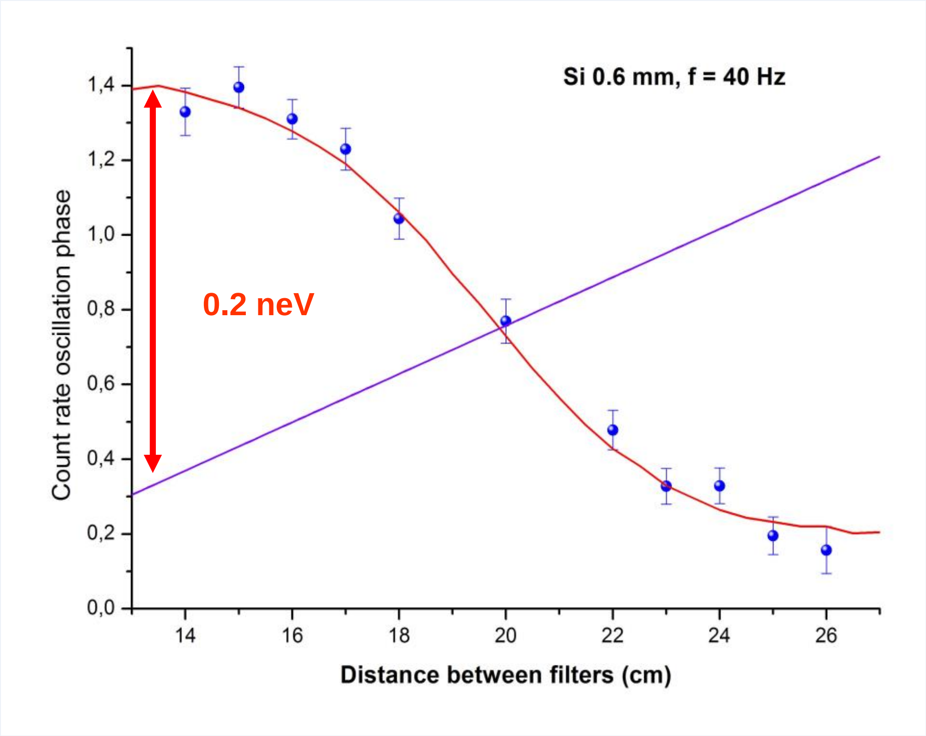




$$w \cong -A\Omega^2 \sin\Omega t \qquad V \cong A\Omega \cos\Omega t$$

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

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



$$w_{max} = A\Omega^2 \approx 60 m/s^2$$

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

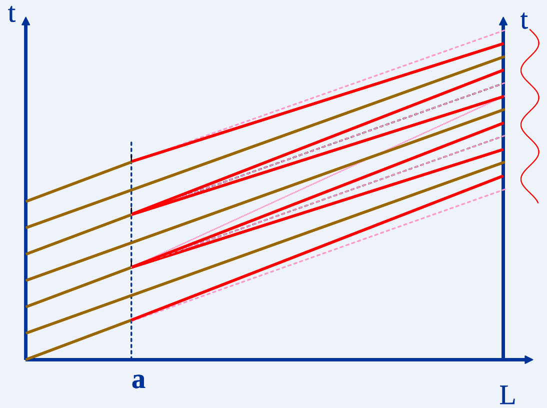
$$K = 0.94 \pm 0.06$$

$$\Delta E = (2 \div 6)\times 10^{-10}$$

$$\Delta\tau \approx 1.5\times 10^{-4}$$

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

Observation of the weak time focusing due to AME

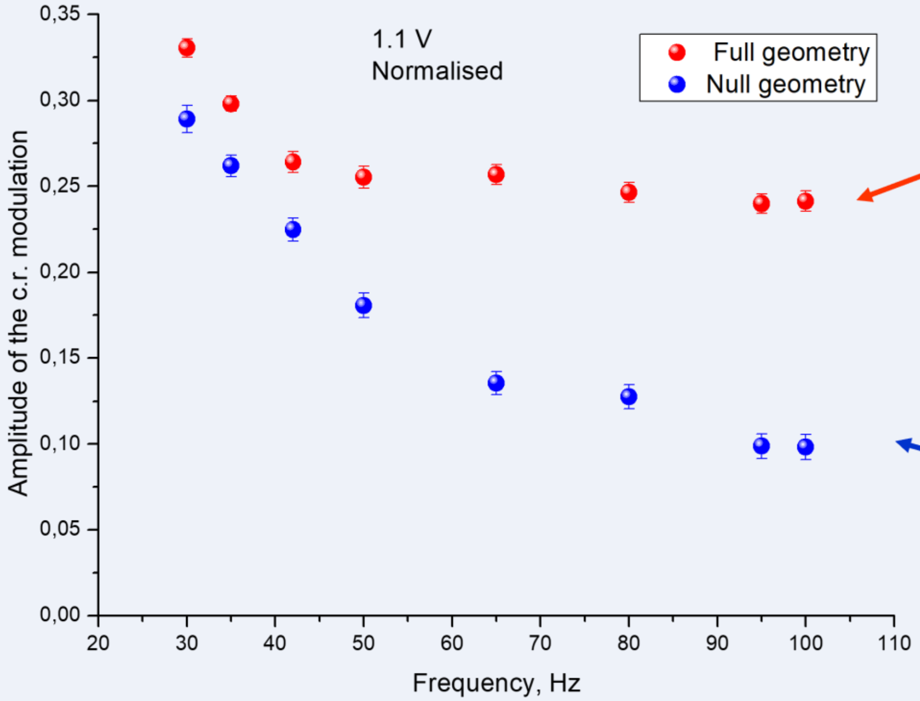


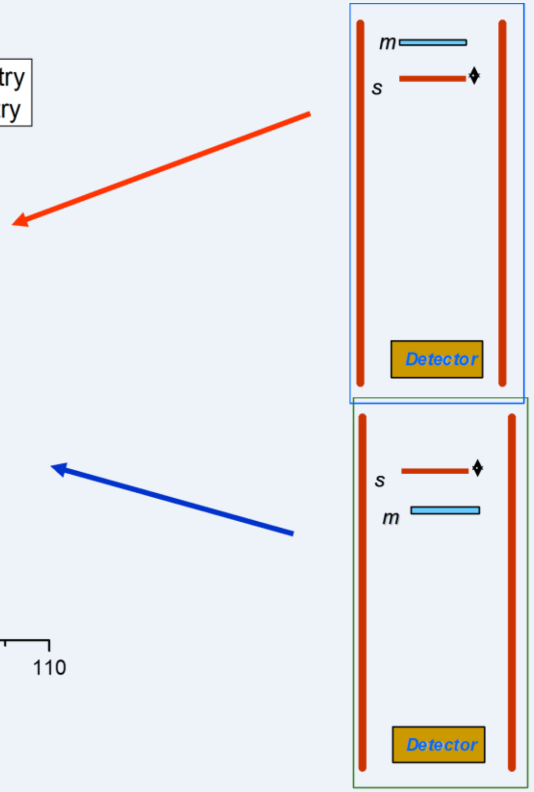
$$w \cong -A\Omega^2 \sin\Omega t$$

$$V \cong A\Omega \cos\Omega t$$

$$V_{max} = \frac{w_{max}}{\Omega}$$

$$w \cong -A\Omega^2 \sin\Omega t$$





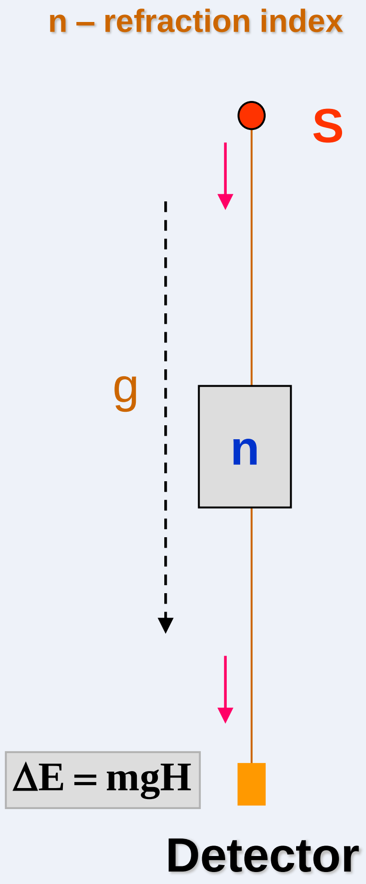
The amplitude of the count rate modulation was measured for the set of Ω at $A\Omega^2$ = const

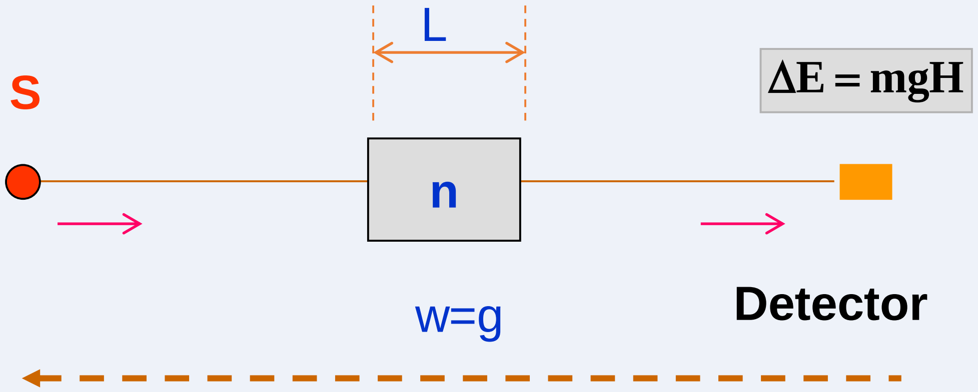
$$\frac{\Delta V_{exp}}{\Delta V_{th}} = 0.95 \pm 0.05_{stat} \pm 0.05_{syst}$$

$$\Delta V \approx 1 cm/s, \ \ V \approx 450 cm/S$$

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

Accelerating sample and the equivalence principle



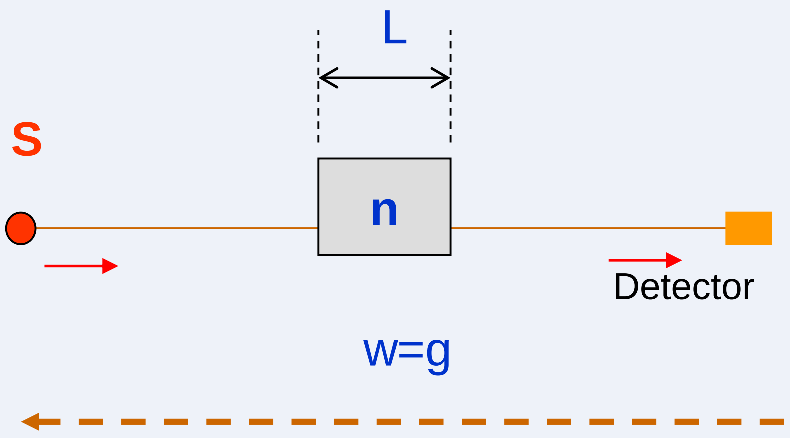


1. **In both cases the energy, measured by the detector, must be the same due to the equivalence principle**
2. **Inserting the refracting slab does not change the energy due to the energy conservation law (see left fig.)**
3. **Delay time due to refraction is $\Delta\tau$**

$$\Delta v = w\Delta\tau$$

During this delay time the detector will continue to accelerate

Accelerating sample and the equivalence principle



$$\Delta v = w\Delta\tau$$

$$|\Delta E| = mv \cdot \Delta v$$

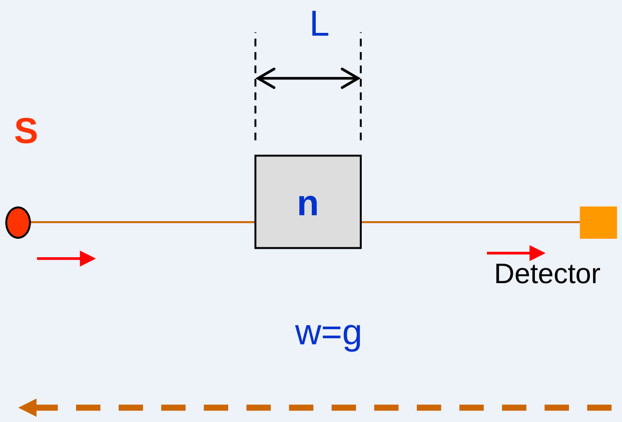
If the time delay $\Delta\tau$ is the only effect associated with the sample, then introduction of (accelerating) sample would result in change in the detected energy which is contrary to the equivalence principle

Consequently, for the validity of the equivalence principle it is necessary that time delay time $\Delta\tau$ due to refraction must be accompanied by the change of energy

We concluded that AME is a very general optical phenomenon, since the concept of the refractive index can be introduced for any particles.

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

Is AME is really just an optical effect?



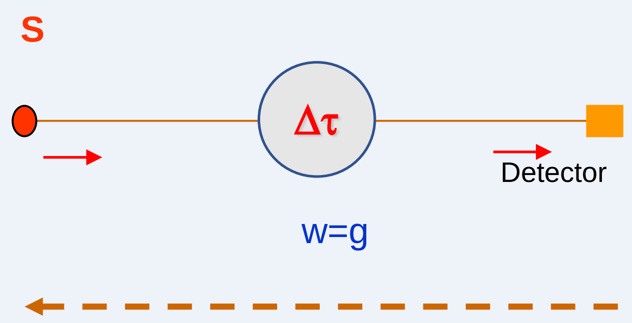
$$\boxed{\Delta v = w\Delta\tau}$$

$$\Delta E = -mv\cdot\Delta v$$

Previously we came to the conclusion that in order to fulfill the equivalence principle, the time delay $\Delta\tau$ arising due to the difference in wave vectors in the vacuum and the sample must be accompanied by a change in energy

But why did we associate the time delay $\Delta\tau$ only with optical phenomena ?

Is AME really just an optical effect?



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But why did we associate the time delay $\Delta\tau$ only with optical phenomena ?

Any interaction is necessarily associated with a time delay

General relation

$$\boxed{\Delta\omega = kw\Delta\tau}$$

Acceleration Effect - formulation

Any object which is scattering a wave or transmitting narrow-band signal shifts the frequency if it is moving with acceleration.

The acceleration effect (AE) is apparently as general as the Doppler effect. However, the frequency shift of the wave is determined not by the speed of the scatterer but by its acceleration

A.I. Frank.. Physics-Uspeckhi, 63, 500-502 (2020)

$$\boxed{\Delta\omega = kw\Delta\tau}$$

w – acceleration
$\Delta\tau$ – time delay (interaction time)

$$\left|E(t+\Delta\tau) - E(t)\right| >> \hbar/\Delta\tau$$

Condition of quasi- classical approximation

Acceleration Effect in neutron and light optics (Acceleration matter effect)

Neutrons

$$k=\frac{mv}{\hbar} \qquad \Delta\tau=\frac{d}{v}\left(\frac{1-n}{n}\right) \qquad \Delta E=\hbar\Delta\omega$$

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

Kowalski-Nosov-Frank

Light, neutrino and ultra-relativistic particles

$$k=\frac{\omega}{c} \qquad \Delta\tau=\frac{nd}{c}-\frac{d}{c}=\frac{d}{c}(n-1)$$

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

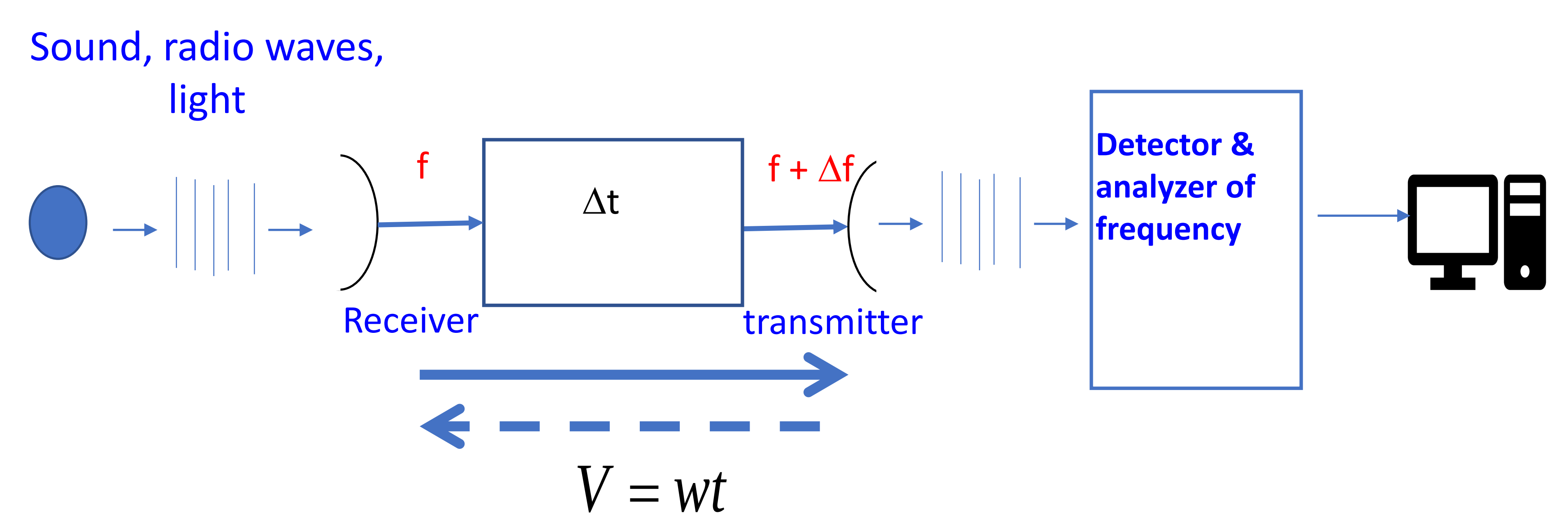
Kazuo Tanaka ,Phys.Rev. A 25, 385 , 1982

$$\boxed{\Delta\omega = kw\Delta\tau}$$

$$|E(t+\tau)-E(t)| \gg \hbar/\tau.$$

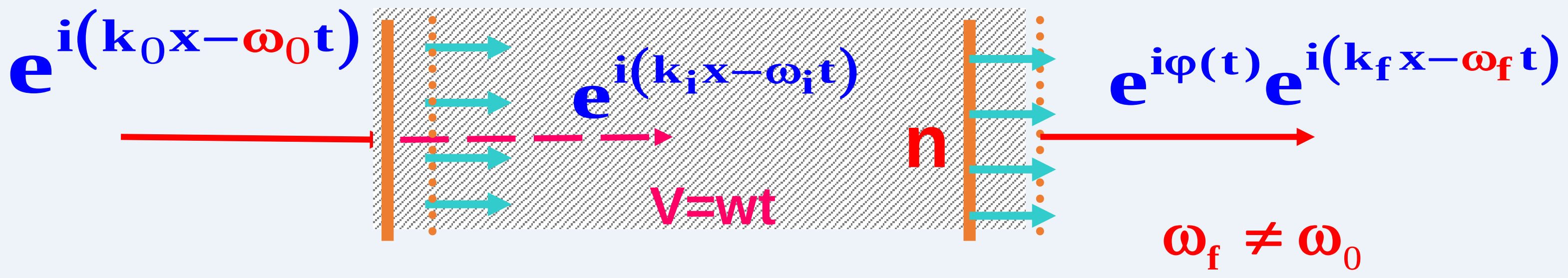
A.I. Frank.. Phys.-Uspeckhi, 63, 500 (2020)

Acceleration effect in classical physics – Differential Doppler Effect



Acceleration effect in optics (Accelerating Matter effect) also may be interpret as a differential Doppler effect

Acceleration effect in optics – Accelerating Matter effect also may me interpret a differential Doppler effect



For the accelerated motion, two Doppler frequency shifts do not compensate each other because the velocity of the medium is not constant.

Neutrons

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

A.I.Frank and V.A.Naumov.
Phys. of Atom. Nuc., 76,1423 (2013)

Doppler shift at refraction

$$V(t+\tau) = V(t) + w\tau$$

Light

$$\omega_i = \omega_0 + \frac{v}{c}(n-1)$$

C. Yeh. J. Appl. Phys. **36**, 3513 (1965)

Transmission of neutrons through an accelerating crystal near the Bragg conditions. It also is differential Doppler effect

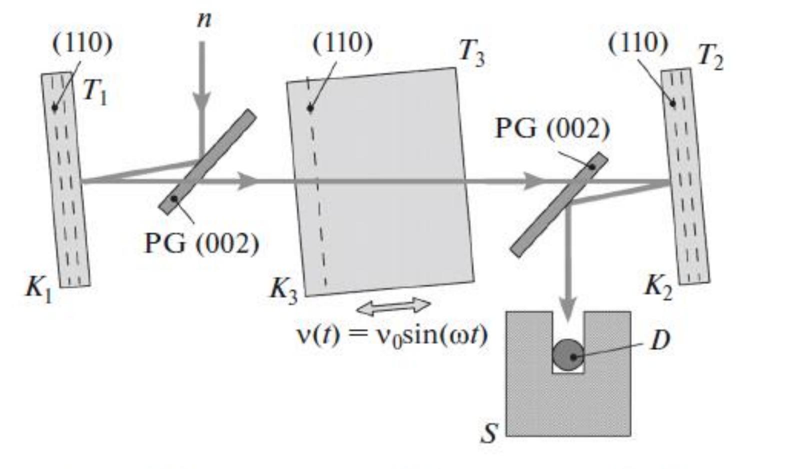


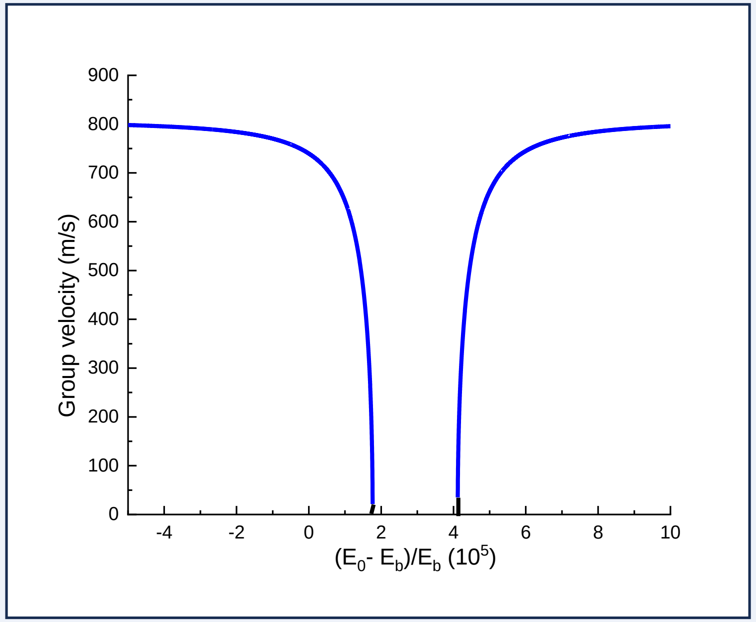
Fig. 1. Scheme of experimental setup: (n) collimated neutron beam, (K_{1-3}) quartz single crystals of temperature T_{1-3}, (PG) pyrolytic-graphite crystals, (D) neutron detector, and (S) detector shield.

$$k = F\left(k_0\right)$$

$$k_0'\left(t\right) = k_0 - mwt$$

$$v = \frac{\hbar k}{m^*} = \frac{\hbar}{2m}\left(\frac{dF}{d\left(k_0'^2\right)}\right)^{-1}$$

I. Frank, G. V. Kulin, and M. A. Zakharov, *Phys. Part. Nuclei Lett.* **22**, 316 (2025)



V.V. Voronin et al., JETP letters, 100, 497 (2014)
Yu. P. Braginetz et al., Phys. At. Nucl. 80, 32 (2017)

$\Delta\tau \approx 10\ \mu s$ $\Delta E \approx 10 neV$

Can the Acceleration effect always be interpreted as the Differential Doppler effect?

It may seem that the acceleration effect always may be interpreted as a differential Doppler effect, when the receiving of a wave and its emission are separated by a time interval during which the velocity of the object changes.

But that is not true in quantum mechanics, where the process of interaction of a particle with an accelerating object (potential structure) can hardly be separated by absorption and radiation phases?

The important question is whether the concept of a universal Acceleration Effect in quantum mechanics is correct.

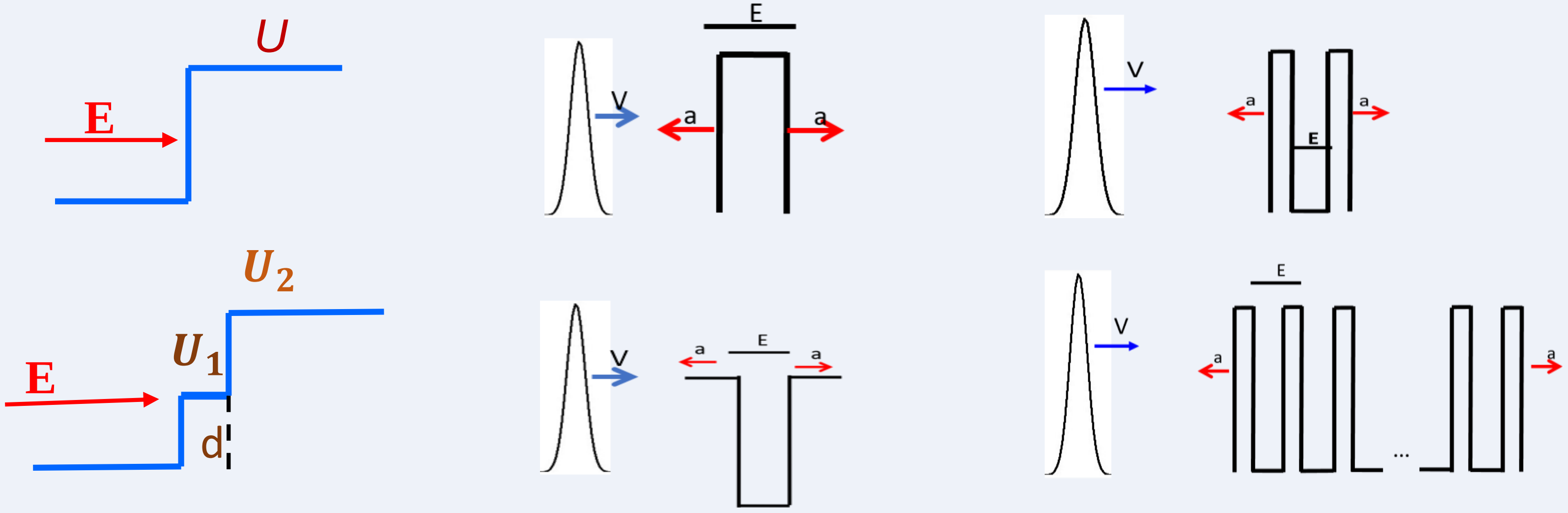
And if this is true, what should be taken as a measure of time delay? $\Delta\omega = kw\Delta\tau$

Assumption: The time delay is determined by Group delay time (GDT) of Bohm-Wigner

$$\boxed{\tau_g = \hbar\left(\frac{d\varphi}{dE_z}\right)}$$

Bohm D., *Quantum Theory*, Prentice-Hall, New York, 1951.
Wigner E.P., Phys. Rev., **98**, 145 (1955).

Numerical calculations based on the method of the evolution operator splitting



M.A. Zakharov, G.V. Kulin, A.I. Frank. Eur. Phys. J. D (2021)

More details will be presented By Maxim Zakharov 29 May

In all cases, the energy of the wave packet changed are in qualitative agreement with $\Delta\omega = kw\Delta\tau$, where Δτ – is interaction time (group delay time)

***Acceleration effect* that complements the Doppler effect, but does not depend on speed, but on acceleration, should take place in quantum mechanics.**

This result awaits experimental confirmation.

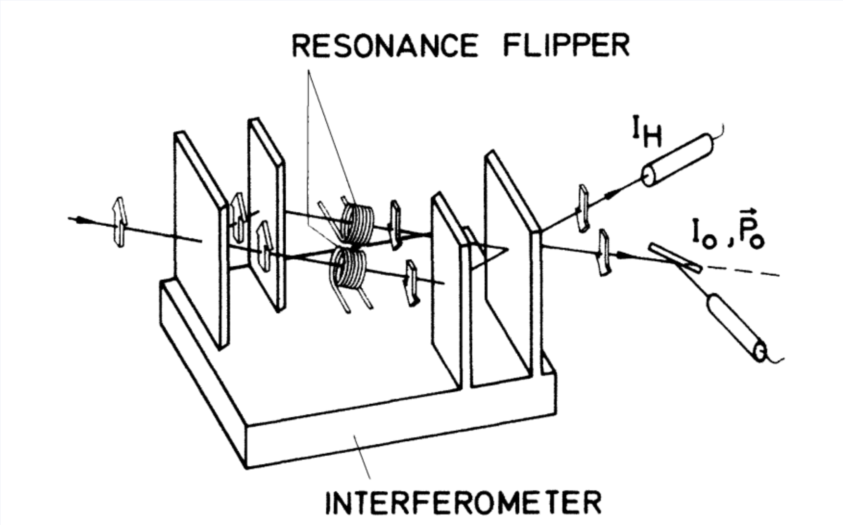
But! Delay time in the theoretical analyzed problems is the three order of magnitude less that it was in previous experiments with UCN

$$\Delta\tau \approx (3 \div 5) \times 10^{-7}\, s$$

How to increase the sensitivity of the experiment?

The idea is: measure not the energy ΔE but frequency Ω

$$\Omega = \frac{\Delta E}{\hbar} \qquad \hbar = 6.6 \times 10^{-16}\,\mathrm{eV} \cdot \mathrm{s}$$



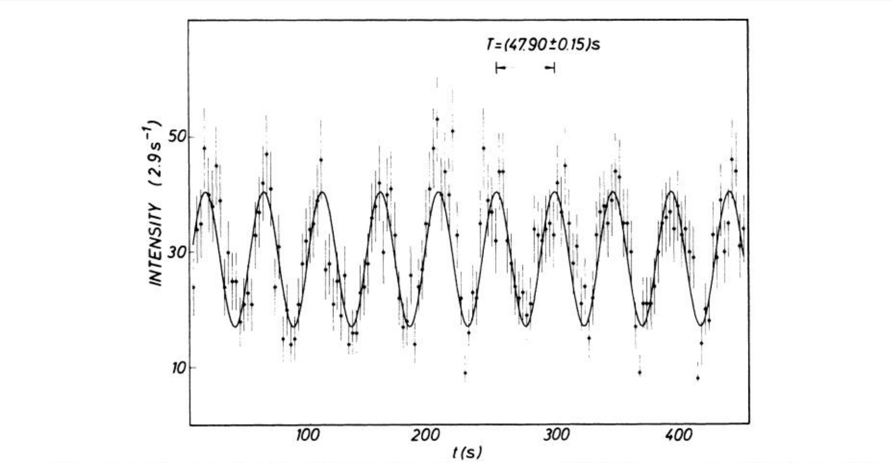


FIG. 6. (a) Real-time beat effect obtained if slightly different frequencies $\nu_{r1}=71.89980$ kHz and $\nu_{r2}=71.89978$ kHz ($\Delta\nu=0.02$ Hz) are applied to both rf coils. The observed beating period corresponds to an energy difference of the interfering beams of 8.6×10^{-17} eV and the energy resolution is determined as 2.7×10^{-19} eV. (b) The beat effect disappears completely if both coils are driven off resonance.

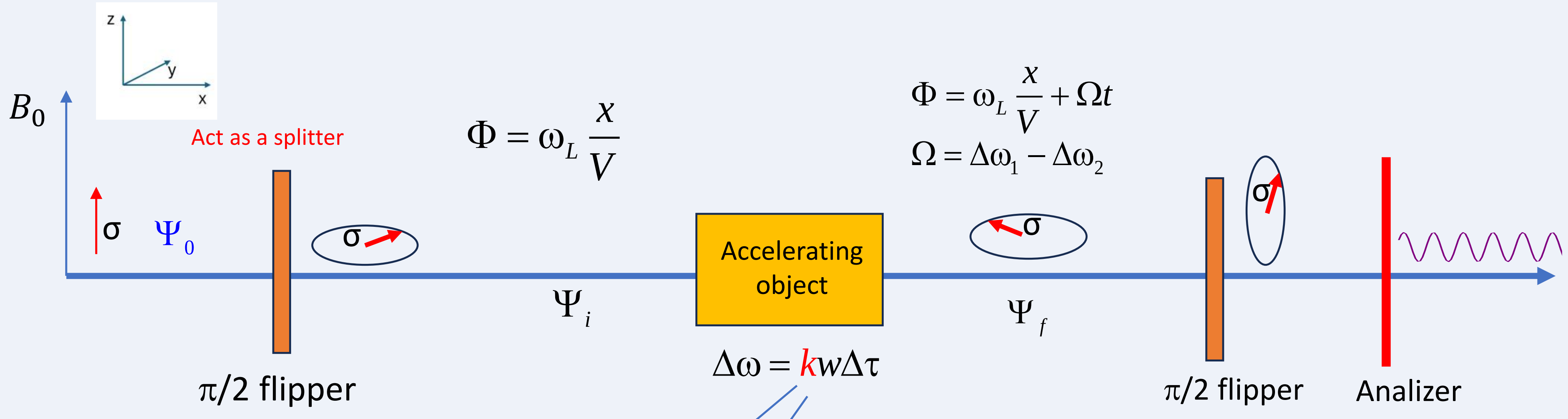
$$\delta E \sim 10^{-16}\,eV$$

G.Badurek, H.Rauch, and D.Tuppinger, Phys.Rev.A , 34 (1986), 2600

Do we need neutron interferometer? Not necessary.

Spin precession may be interpreted as a result of the two spin states interference

Two-wave Acceleration effect and nonstationary spin precession



$$\Psi_0(x,t) = \exp\left[i(kx-\omega t)\right]$$

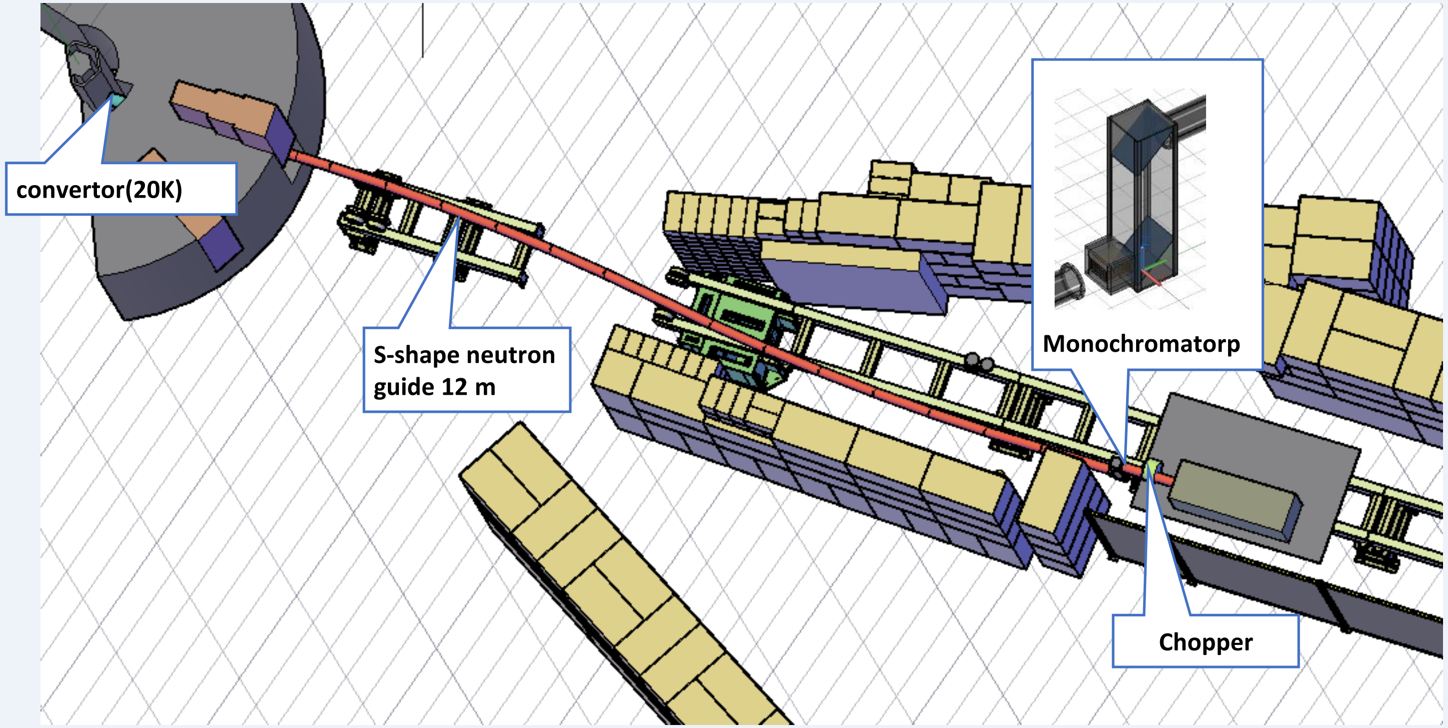
$$\Psi_i(x,t) = \frac{1}{\sqrt{2}}\begin{pmatrix} e^{+\Delta kx} \\ e^{-\Delta kx} \end{pmatrix}\Psi_0$$

$$\Psi_f(x,t) = \frac{1}{\sqrt{2}}\begin{pmatrix} e^{+\Delta kx+\Delta\omega_1} \\ e^{-\Delta kx+\Delta\omega_2} \end{pmatrix}\Psi_0$$

$$\varphi(t) = \Omega t \qquad \delta E = \hbar\Omega \qquad \Delta E = \hbar\Delta\omega \qquad \Delta\omega = \bar{k}w\Delta\tau$$

A I Frank , P Geltenbort, M Jentschel, et al. Journ.of Phys.: Conf. Series 340 (2012) 012042.
A.I.Frank, V.A.Naumov. Phys. At.Nuc., 76 (2013), 1423; A.I.Frank. Journal of Physics: Conf. Ser. **711** (2016) 012016.

First experiments may be performed at the VCN source of IBR-2 reactor which is under construction now.



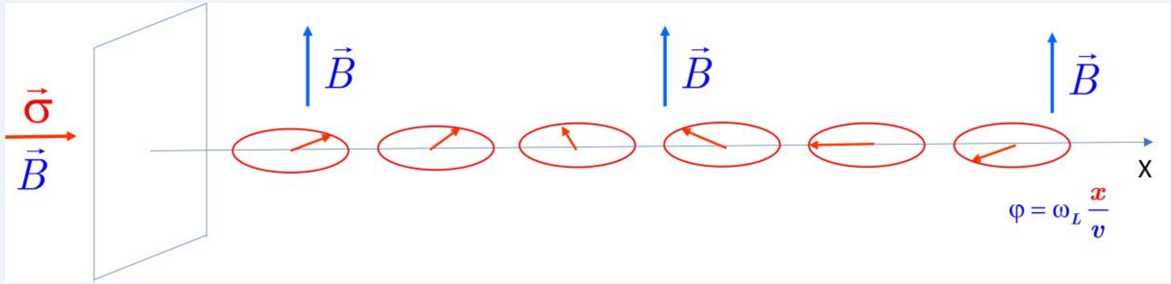
$$V = 20 \text{ m/s} \quad (\lambda = 20\text{nm})$$

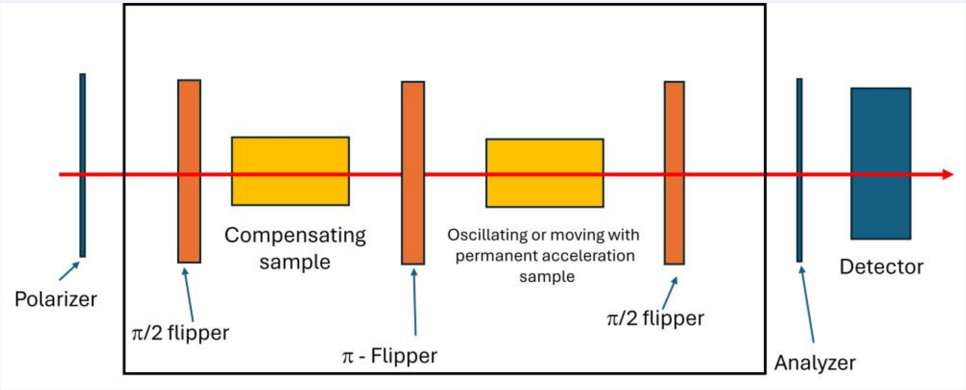
$$\frac{\Delta\lambda}{\lambda} \approx 0.07$$

(Talk of A.Popov, 29 May)

Two possible approaches to the realization experiment for the observation AE in the case of birefringence

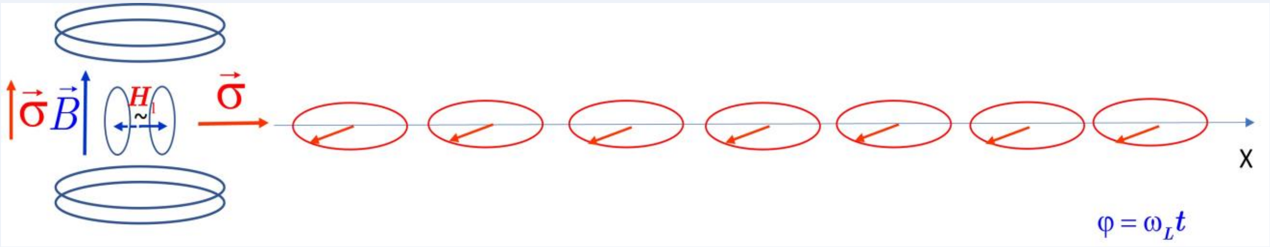
a) Initial state was prepared with help of stationary device. In the point of observation spin is not rotating

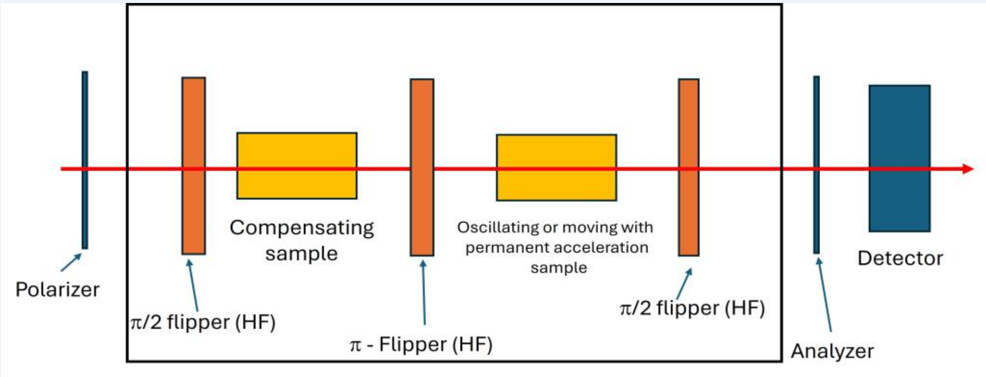




Classical Spin-Echo

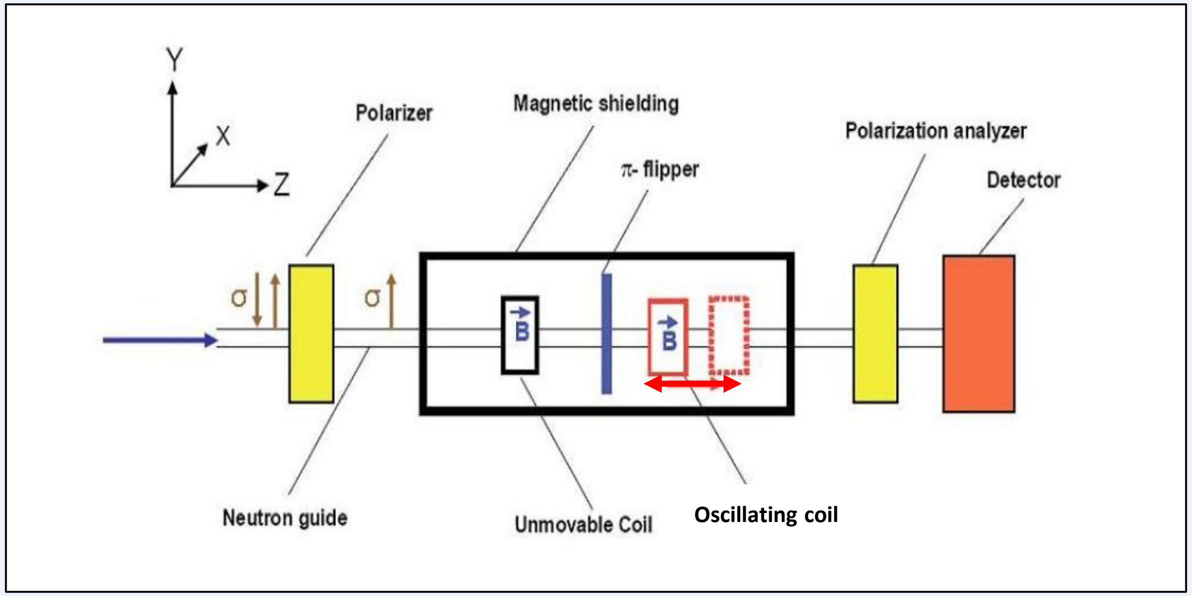
b) Initial state was prepared with help of nonstationary device. In the point of observation spin is rotating

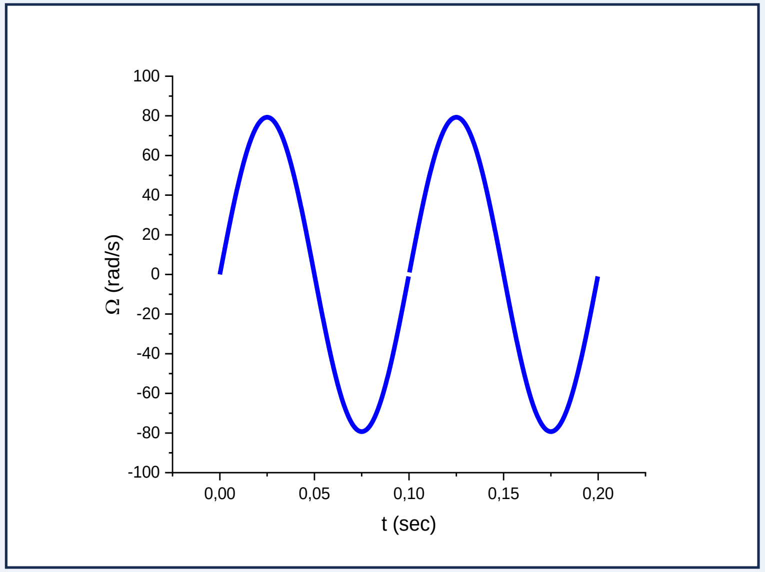




Resonant Spin-Echo (time interferometry)

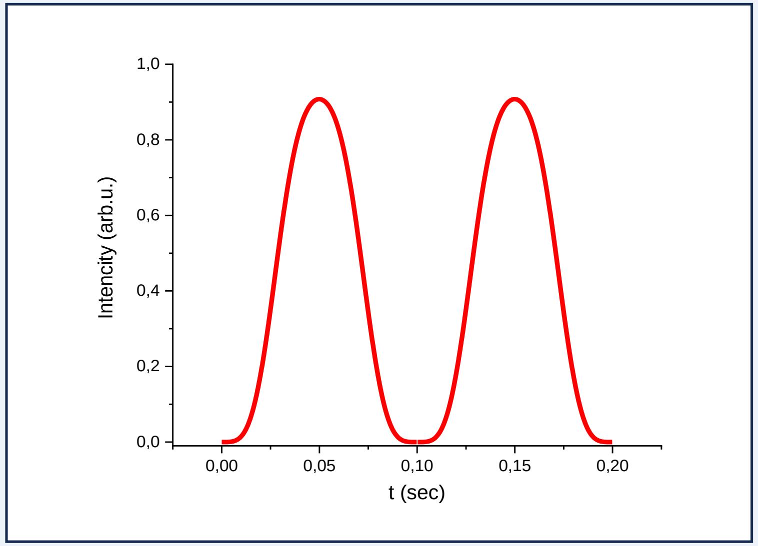
Proof-of principle experiment with VCN.
Region with magnetic field as a sample



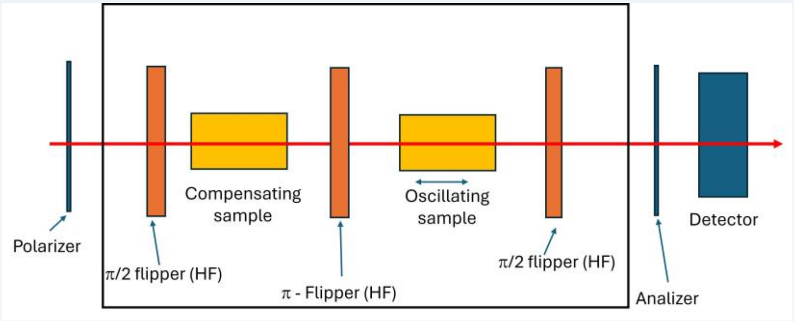


$$\Omega = \omega_L \frac{mwd}{2E}$$

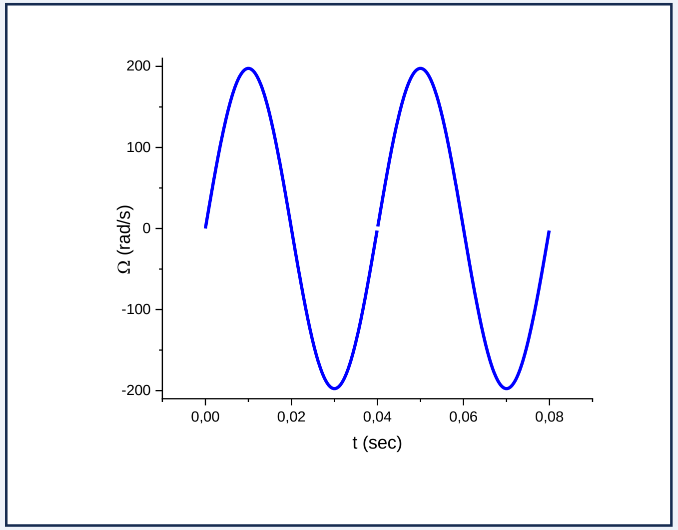
VCN λ= 20 nm
V=20 m/c
B=30 Gauss
d =3cm
The sample oscillating in space $x = a\sin(2\pi f \cdot t)$
f = 10Hz
a = 0.05 cm
Maximal acceleration $w_{max} = 2$ m/s^2



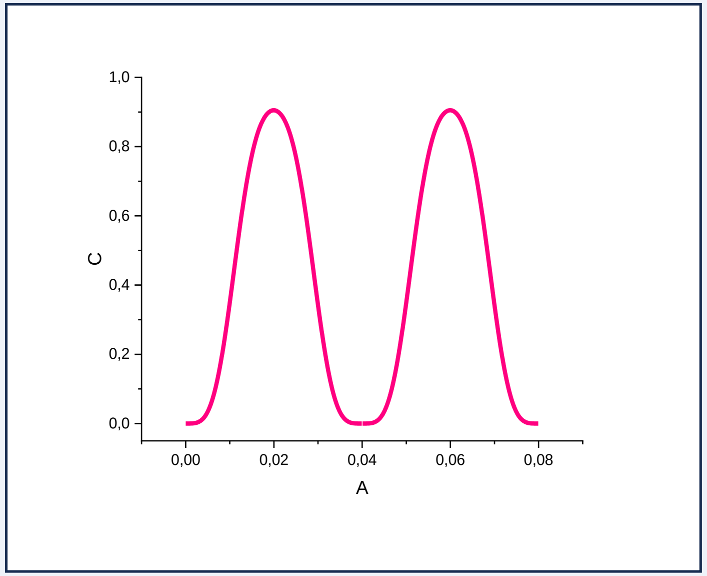
Acceleration effect in the case of birefringent II. Oscillating sample.



VCN λ= 20 nm
V=20 m/c
B(in flipper) =500 Gauss
d =1cm
Effective potential U-150 neV
Sample is oscillating in space
f = 25Hz $x = a\,sin\left(2\pi f \cdot t\right)$
a = 0.05 cm
Maximal acceleration w_{max} =12 m/s^2



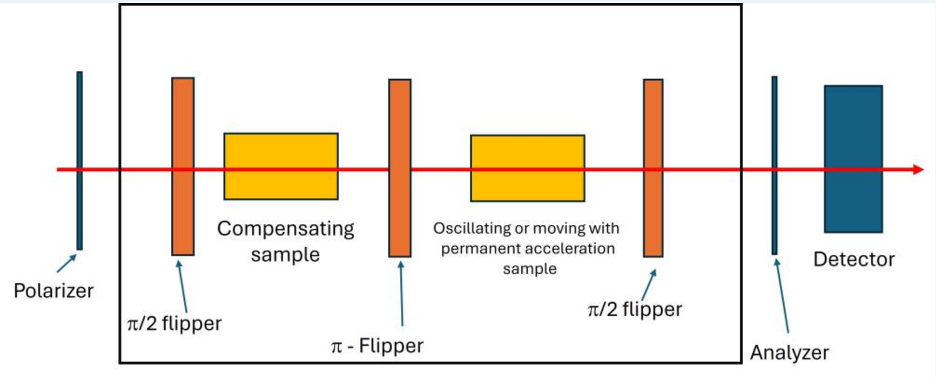
$$\boxed{\Omega = \omega_L mwd \frac{U}{2E^2}}$$



$$\Delta E \approx kw\Delta\tau = 5\times10^{-11}\text{eV}$$

$$\delta E = \hbar\Omega_{max} = 1.3\times10^{-13}\text{eV}$$

Acceleration effect in the case of birefringent III. Oscillating Sample moving with constant acceleration

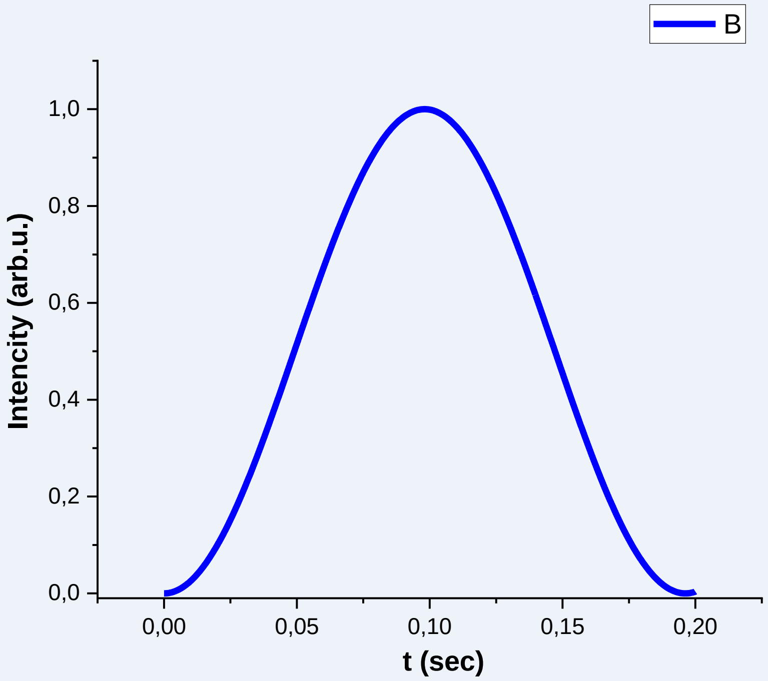


VCN λ= 20 nm
V=20 m/c
B(in flipper) =1000 Gauss
d =1cm
Effective potential U-150 neV
Permanent acceleration
W = 1 m/s^2
Time od moving 0.2 s
S = 2 cm
Ω =32 rad/s

$$\boxed{\Omega = \omega_L mwd \frac{U}{2E^2}}$$

$$\Delta E \approx kw\Delta\tau = 3.7\times10^{-12}\,\text{eV}$$

$$\delta E = \hbar\Omega_{max} = 2\times10^{-14}\,\text{eV}$$



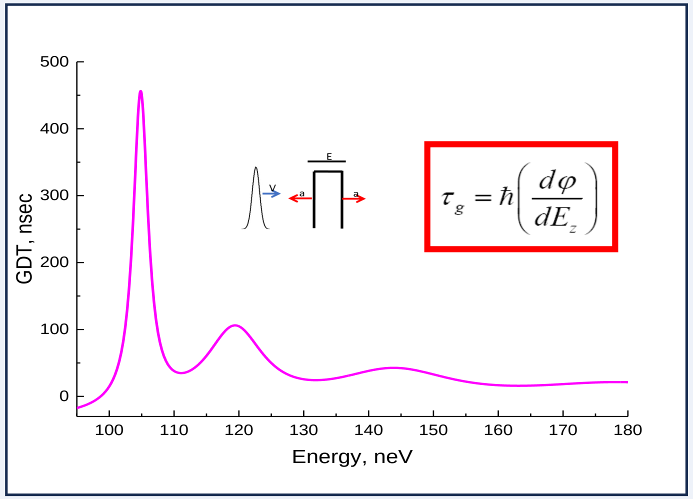
Observation of acceleration effect in the case of birefringence with VCN and UCN

The case of the refractive sample

$$\Omega = \omega_L mwd \frac{U}{2n^3 E^2}$$

The general case $\tau(k)$

τ - delay time



$$\Omega = \omega_L w \frac{m}{\hbar}\left(\frac{\tau}{k} + \frac{d\tau}{dk}\right)$$

Estimated sensitivity to the energy transform due to AE $\Delta E = 10^{-14}\,\mathrm{eV}$

The possibility to observe AE for the artificial potential structures $(\Delta t < 10^{-7} s)$

Conclusion

In agreement with hypothesis of Acceleration Effect (AE) any object that scatters a wave or receives and then emits a signal shifts frequency of the wave if it is moving with acceleration.

That was conformed experimentally only for the optical Effect of Acceleration Matter.

It is extremely important to test the validity of the AE concept for the wave scattering by a quantum objects. It is a difficult task due to smallness of the energy transform

To increase sensitivity of such experiment we propose to observe Acceleration effect under condition of nonstationary spin precession (Two-wave Acceleration effect).

Experiments with registration of neutron energy transform due to AE at the level of several peV can be performed with the VCN source at the IBR 2 reactor

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Thank you for your attention !