The equivalence principle and acceleration effect

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Outline

- Introduction: two optical effects which seems related
- Discovering of Accelerating matter effect
- Acceleration effect and The Equivalence principle
- Acceleration effect and differential Doppler effect
- Acceleration effect and quantum mechanics
- Neutron scattering on an accelerating nucleon and open questions in neutron optics
- Plans and intentions
- Conclusion

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

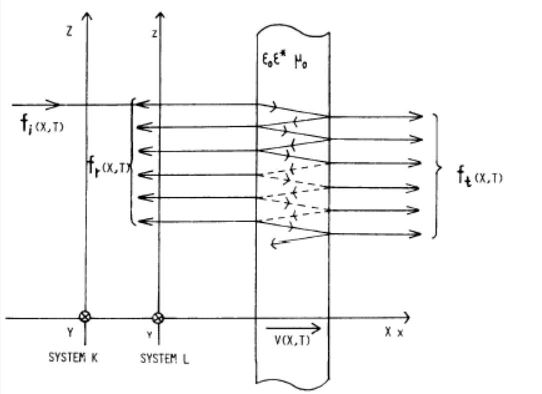


FIG. 1. Geometry of the problem.

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

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

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

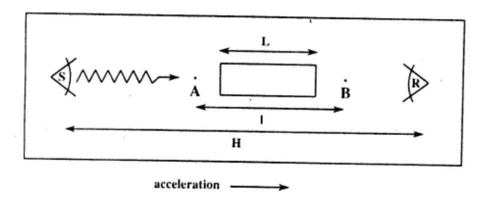


Fig. 1. The source, S, emits a neutron which propagates through the slab of material to the receiver, R. The slab, S, and R all accelerate rigidly with constant acceleration g in the direction shown. Points A and B are fixed in the inertial frame discussed in the text.

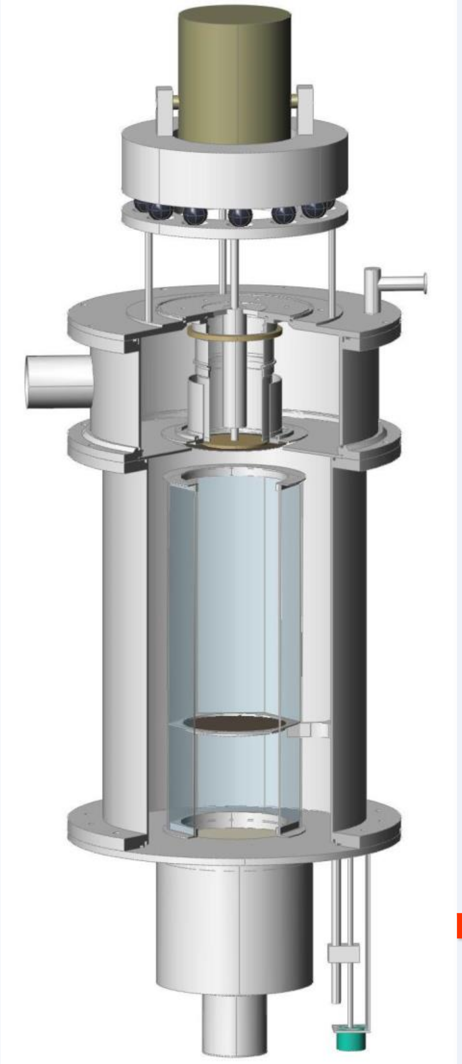
He founded a contradiction with the equivalence principle when calculated the problem but the effect of energy changes was predicted

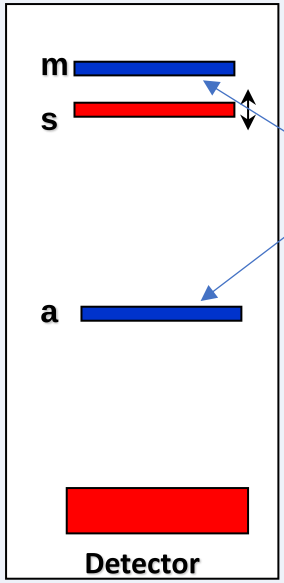
$$\Delta E \cong mwd\left(\frac{1}{n}-1\right)$$

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

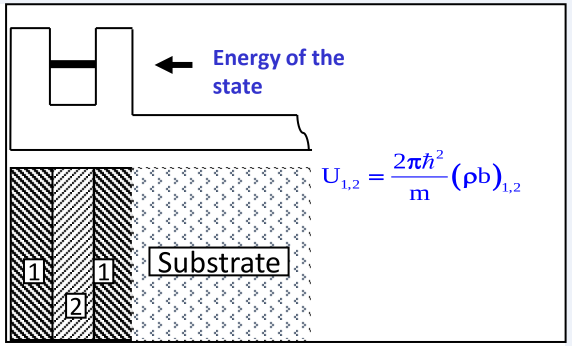
Precise UCN spectrometry

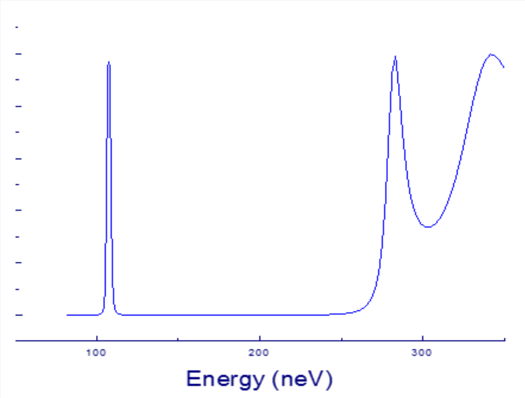


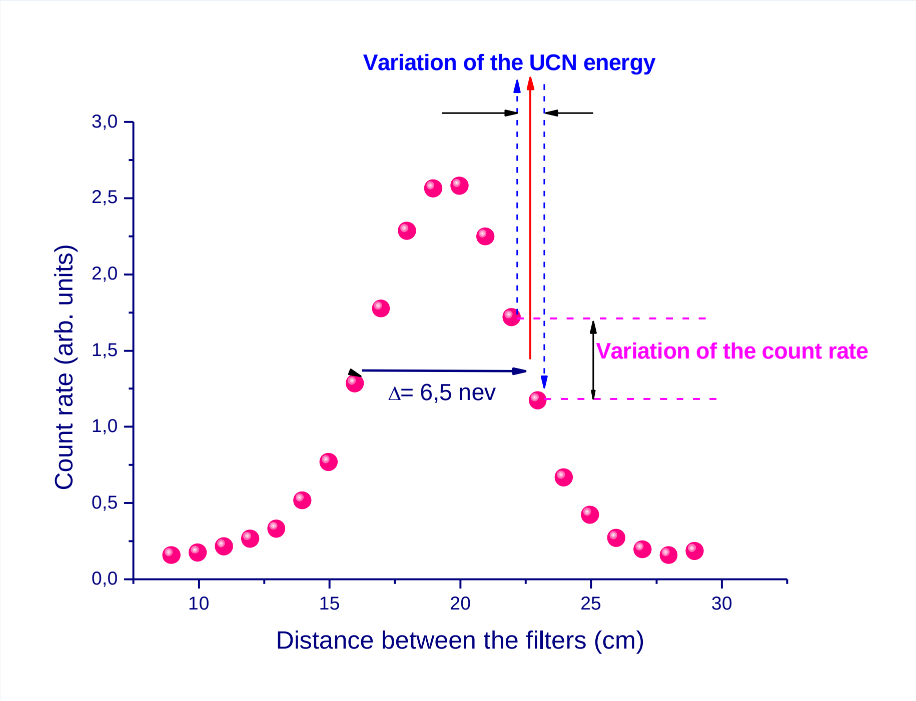


NIF

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





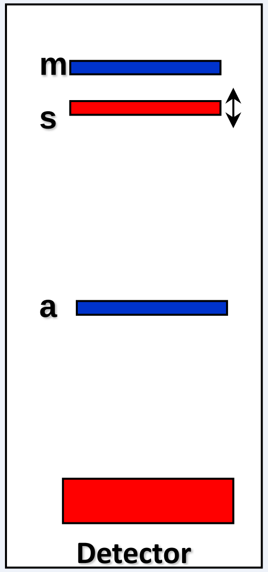


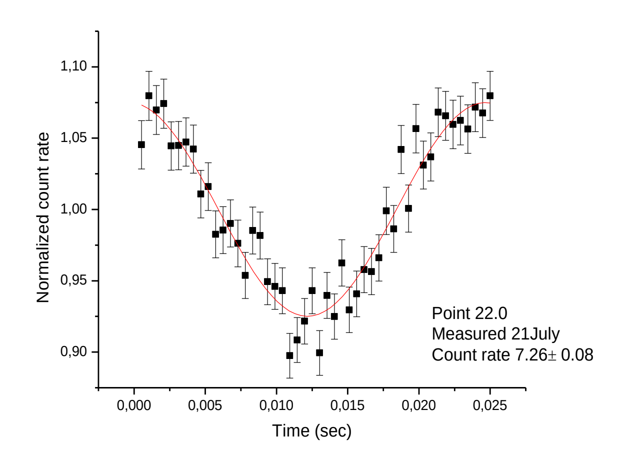
mg=1.02 neV/cm

$\Delta E \approx (2\text{-}5)\times 10^{-10}$ eV

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

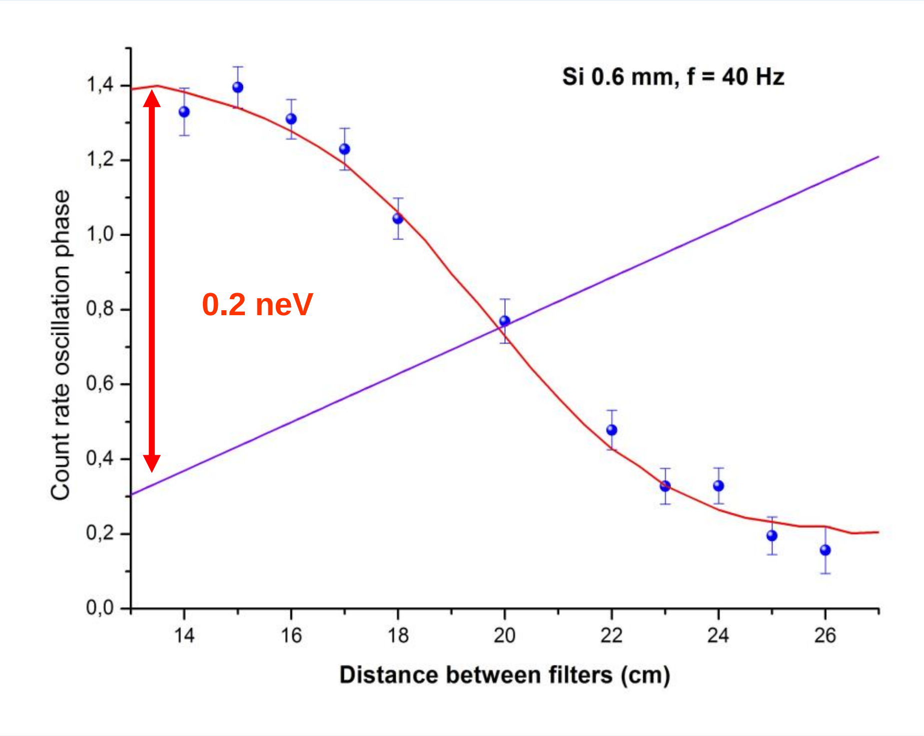




$w \cong -A\Omega^2 \sin\Omega t$ $\quad V \cong A\Omega \cos\Omega t$

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

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



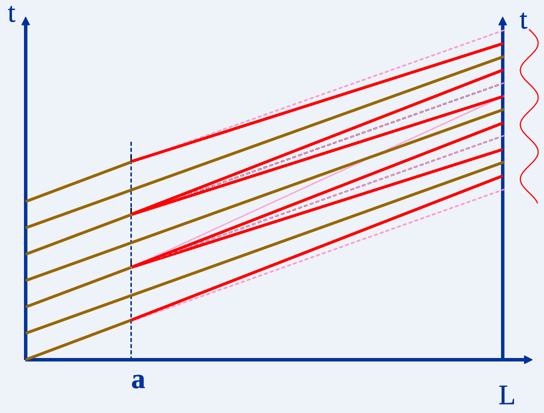
$$w_{max} = A\Omega^2 \approx 60 m/s^2$$

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

$$K = 0.94 \pm 0.06$$

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

Observation of the weak time focusing due to AME

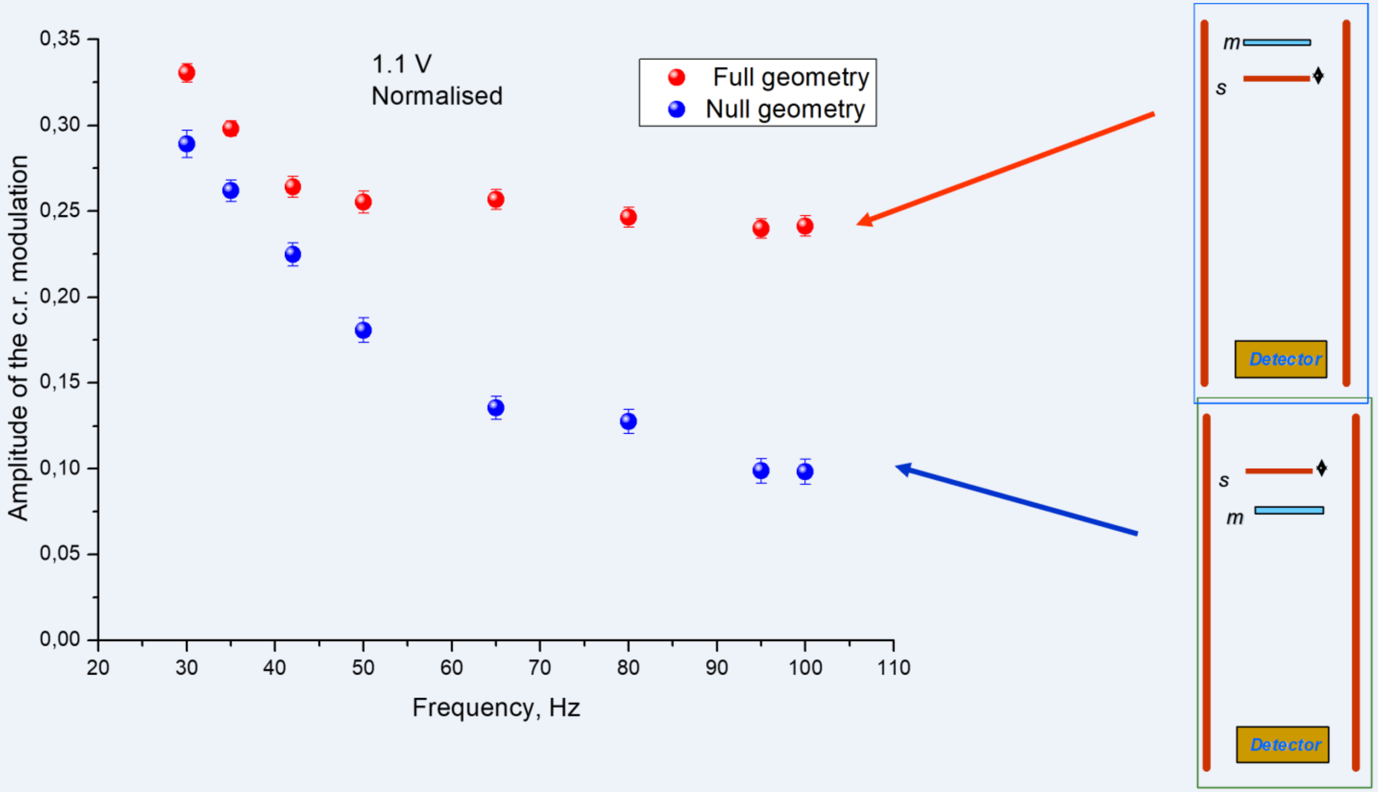


$$w \cong -A\Omega^2 \sin\Omega t$$

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

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

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

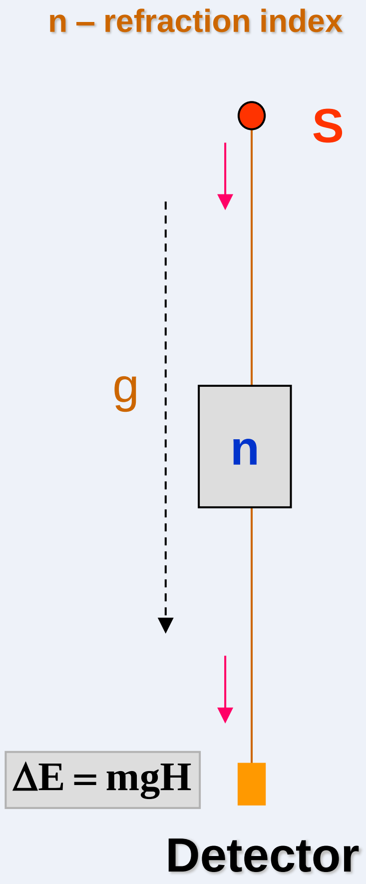


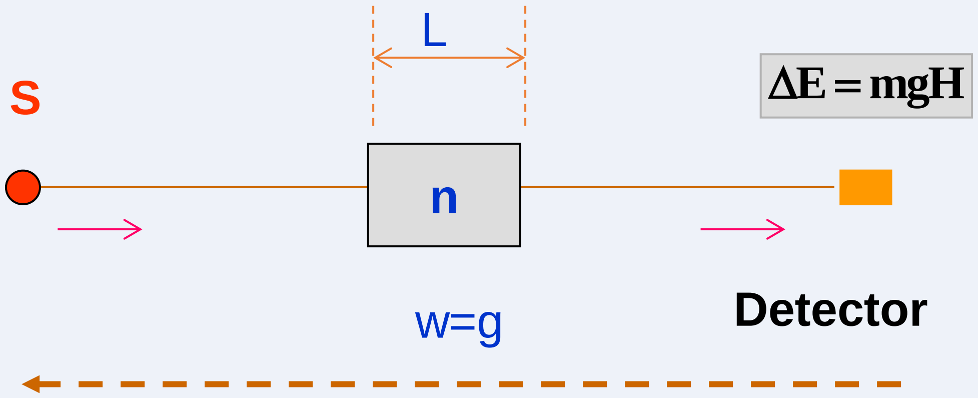
The amplitude of the count rate modulation was measured for the set of Ω at $A\Omega^2$ = const

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

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

Accelerating sample and the equivalence principle



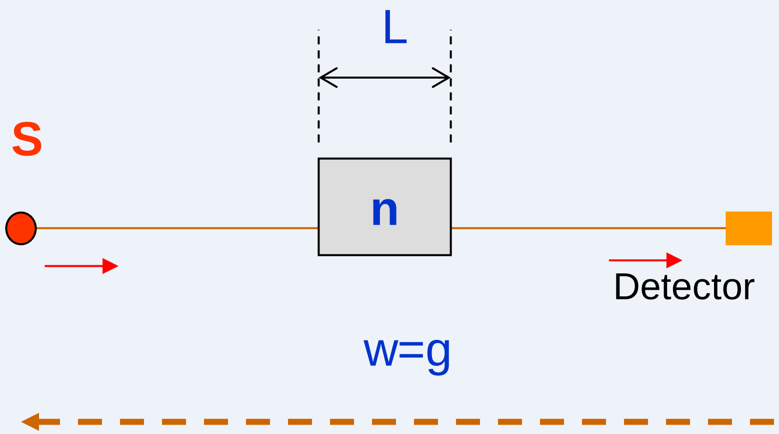


1. In both cases the energy, measured by the detector, must be the same due to the equivalence principle
2. Inserting the refracting slab does not change the energy due to the energy conservation law (see left fig.)
3. Delay time due to refraction is $\Delta\tau$

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

During this delay time the detector will continue to accelerate

Accelerating sample and the equivalence principle



$$\Delta v = w\Delta\tau \qquad |\Delta E| = mv \cdot \Delta v$$

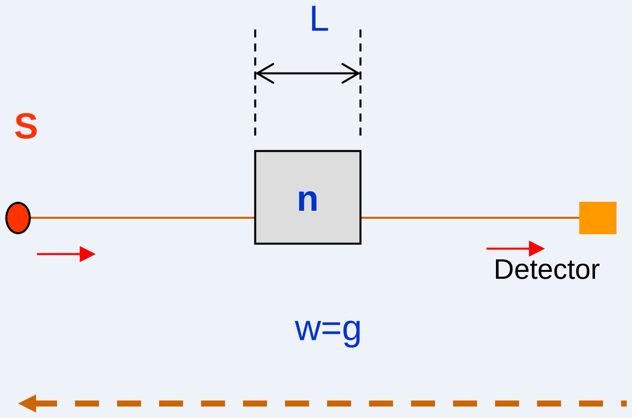
If the time delay $\Delta\tau$ is the only effect associated with the sample, then introduction of (accelerating) sample would result in change in the detected energy which is contrary to the equivalence principle

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?



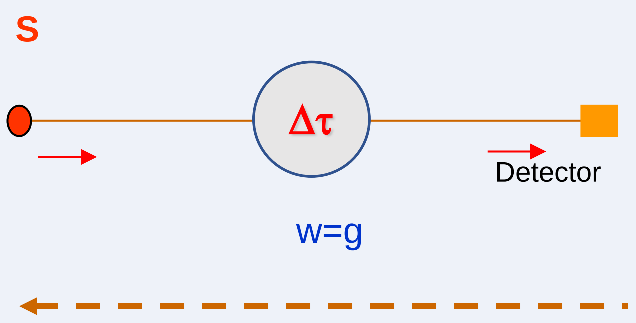
$$\Delta v = w\Delta\tau$$

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

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

$$\Delta\omega = kw\Delta\tau$$

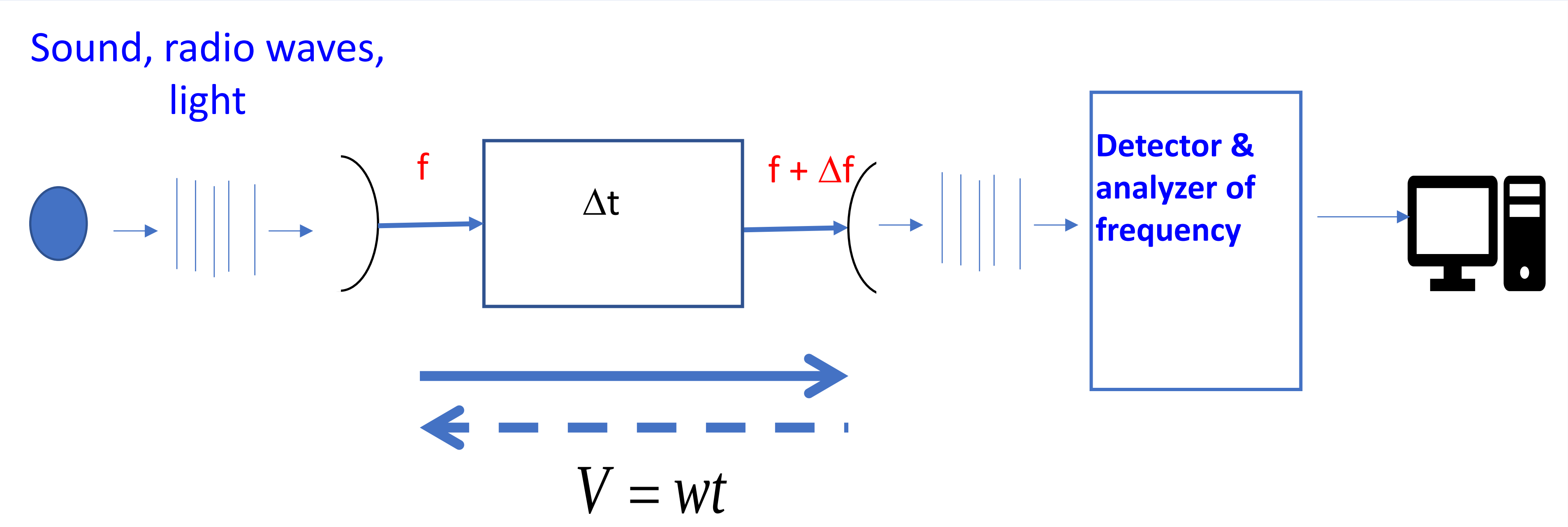
Acceleration Effect

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)

Acceleration effect in classical physics – Differential Doppler Effect



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

$$\Delta\omega = kw\Delta\tau$$

Neutrons

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

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

KNF formula

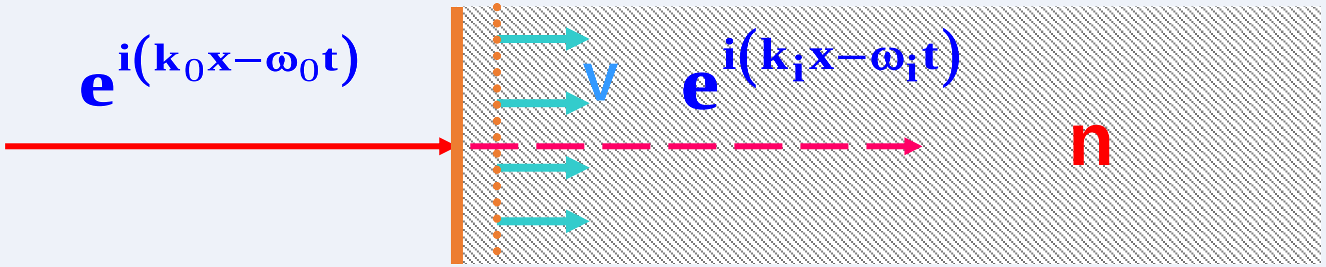
Light, neutrino and ultra-relativistic particles

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

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

Tanaka formula

Refraction of a wave at the border of the moving matter



$$k_i = nk_0\left(1 + \frac{1-n}{n}\frac{V}{v_0}\right)$$

Massive particle (neutron)

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

Doppler shift at refraction

Light

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

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

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

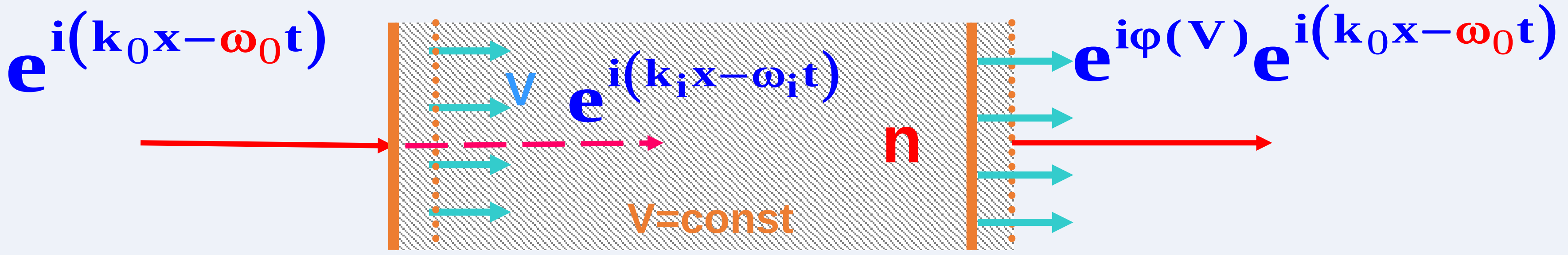
C. Yeh. J. Appl. Phys. **36**, 3513 (1965)

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

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

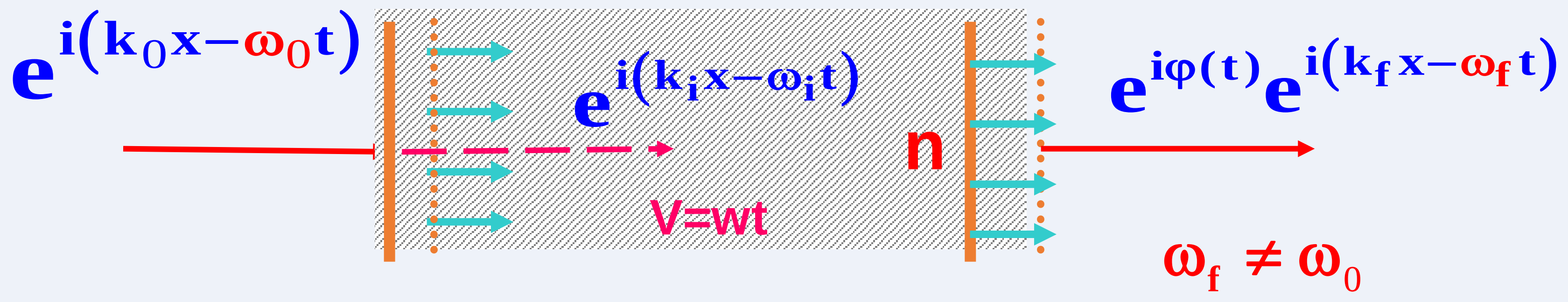
Fresnel drag

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



When the wave enters the sample from free space, its frequency changes. When the wave exit the medium into free space, the frequency of the wave also changes but this change has the opposite sign. When moving at a constant speed, these two frequency shifts compensate for each other.

Transmission of a wave through the moving sample (accelerated motion)



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

Calculations based on the concept of differential Doppler shift leads to the formula:

$$\Delta E \cong mwd\frac{1-n}{n}$$

Kowalski-Nosov-Frank

Assumptions:

1) Quasi – classical approach is correct

2) The model of effective potential is also valid in the case of accelerating matter

Differential Doppler effect and Accelerating Matter Effect at refraction of light

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

??

$$\Delta\omega = \frac{\omega w d n}{c^2}(n-1)$$

Tanaka result and Acceleration effect

Differential Doppler effect

The discrepancy probably occurred because
the fact of the (accelerating) movement of the medium was not taken into account

Transmission of neutrons through an accelerating crystal near the Bragg conditions. Is it also differential Doppler effect?

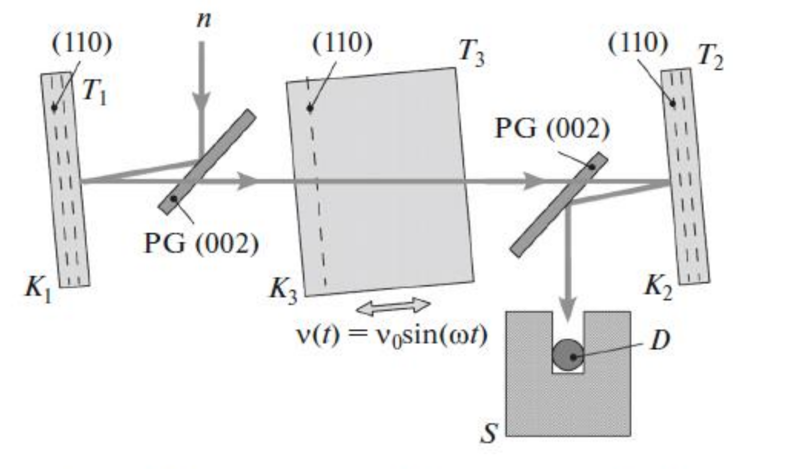


Fig. 1. Scheme of experimental setup: (n) collimated neutron beam, (K_{1-3}) quartz single crystals of temperature T_{1-3}, (PG) pyrolytic-graphite crystals, (D) neutron detector, and (S) detector shield.

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

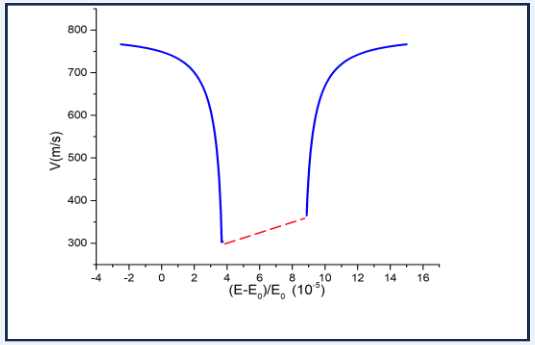
Change of the neutron energy at its transmission through the accelerating crystal in the condition of the Bragg diffraction was detected

The observed effect can be explained in the framework of differential Doppler shift at the boundary of a moving matter. But calculations are more complicated than in the case of refraction.

$$k = F(k_0)$$

$$k_0'(t) = k_0 - mwt$$

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



The authors of the work have a different point of view regarding the nature of the effect.

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

It seems that the acceleration effect always may be interpreted as a differential Doppler effect, when the absorption of a wave and its emission are separated by a time interval during which the velocity of the object changes. Although sometimes the calculations are not entirely trivial

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.

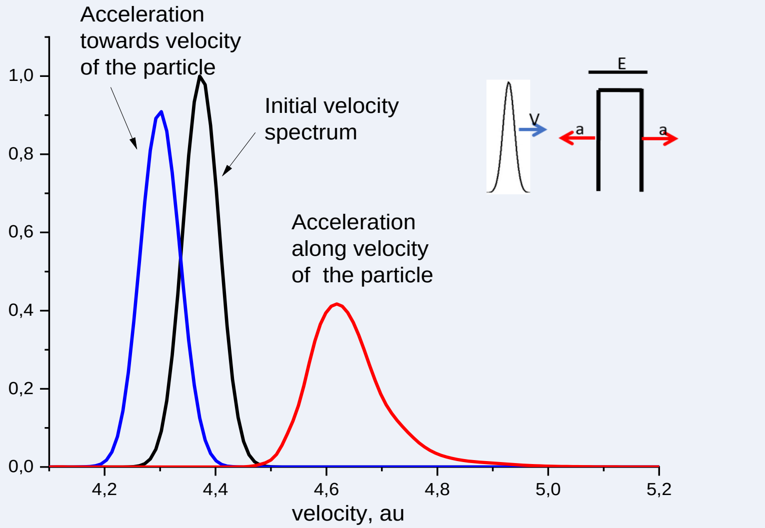
And if this is true, what should be taken as a measure of time delay? $\Delta\omega = kw\Delta\tau$

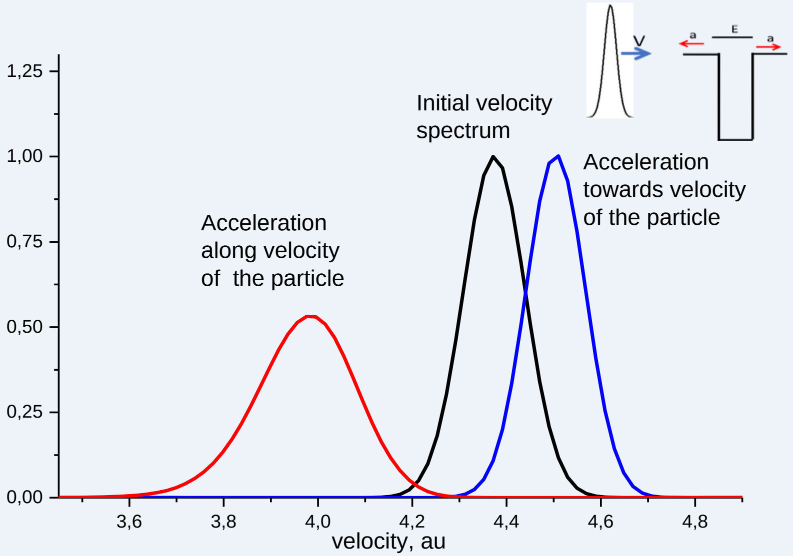
Assumption: The time delay is determined by Group delay time (GDT) of Bohm-Wigner

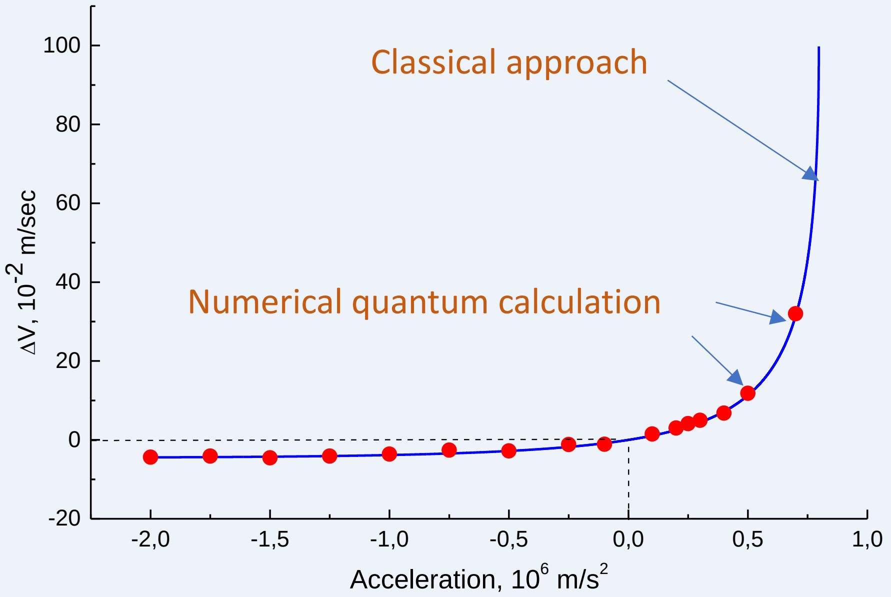
$$\tau_g = \hbar\left(\frac{d\varphi}{dE_z}\right)$$

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

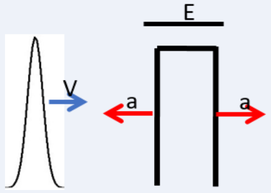


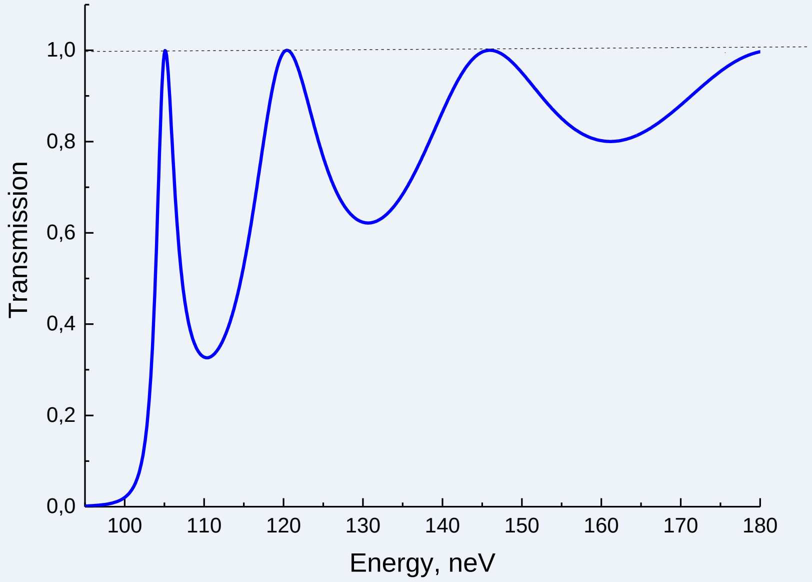


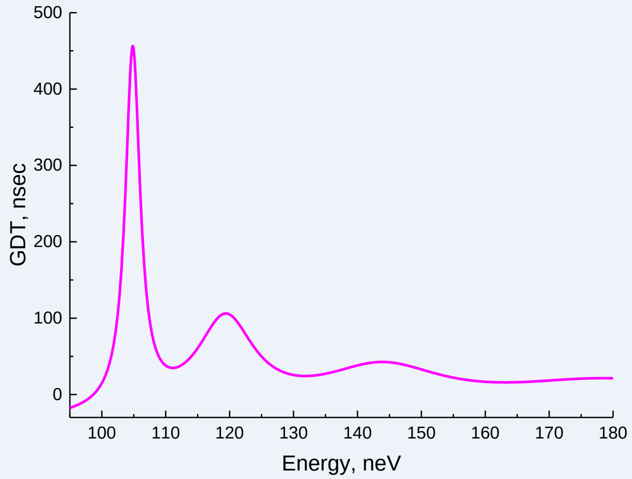


M. A. Zakharov, G. V. Kulin, and A. I. Frank. Eur. Phys. *J. D* **75,** 47 (2021).

The Acceleration Effect when a neutron passes through a potential structure moving with acceleration. Under the barrier passage. The interference effects are significant.

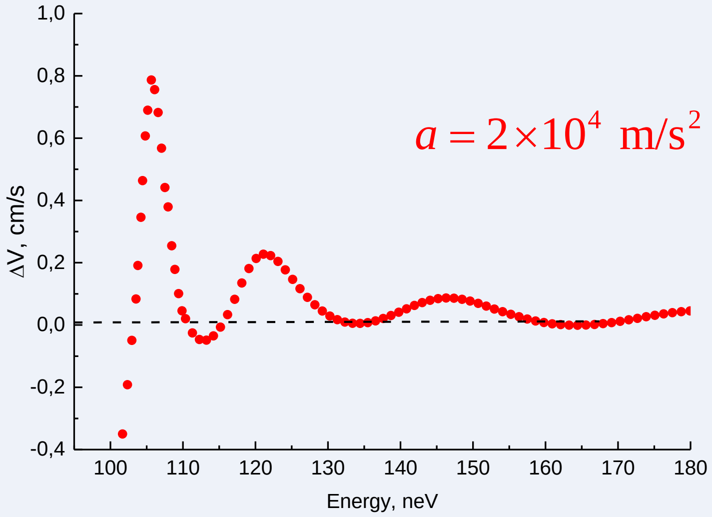






$$\tau_g = \hbar\left(\frac{d\varphi}{dE_z}\right)$$

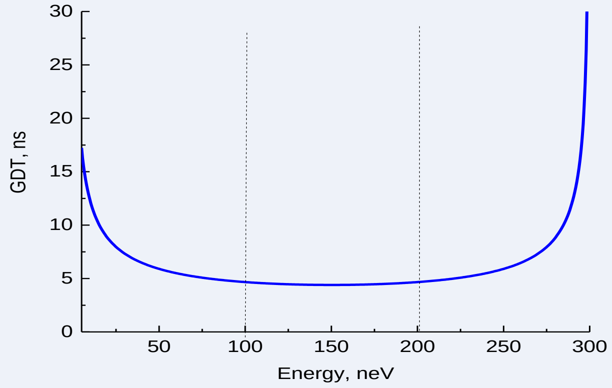
Group delay time (GDT)

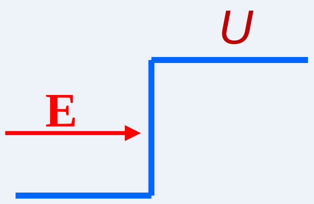


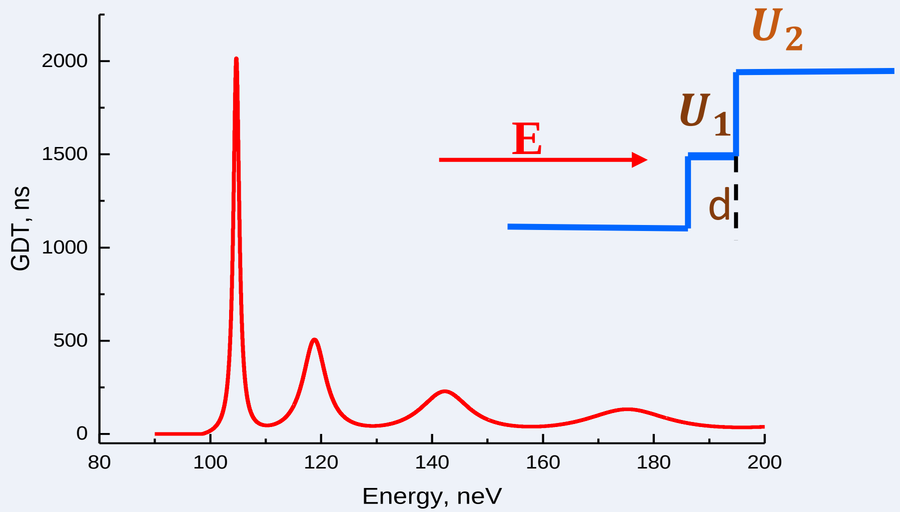
$$\Delta v \approx w\tau$$

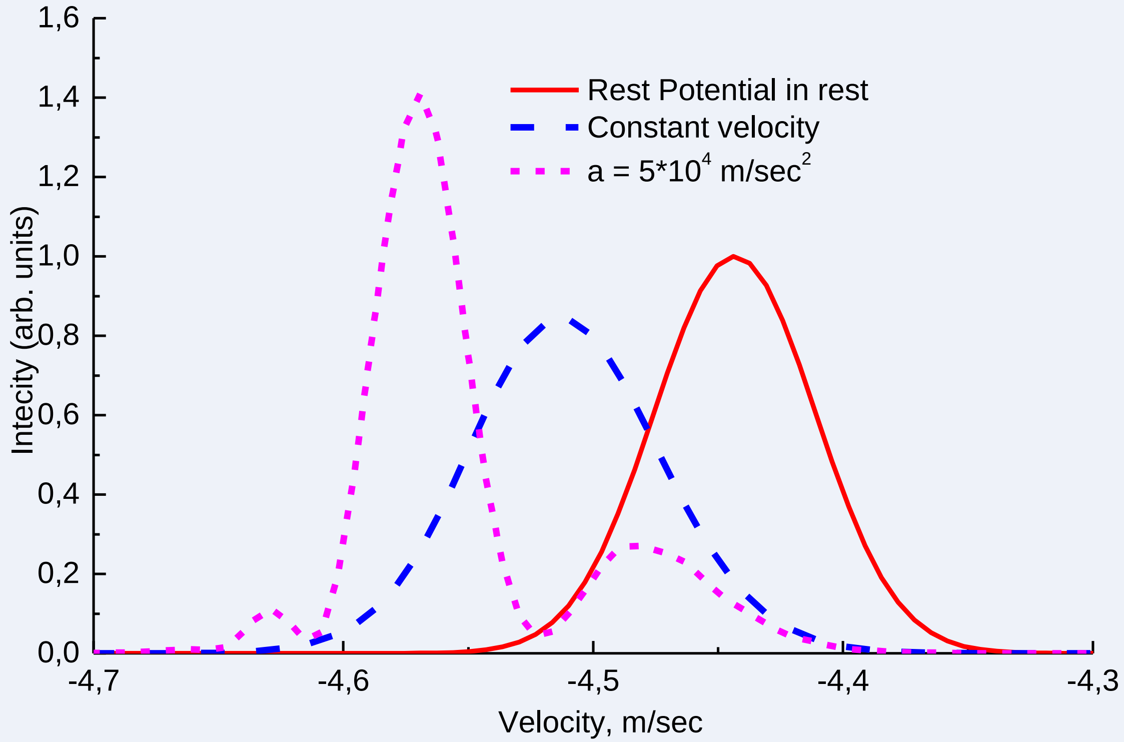
M. A. Zakharov, G. V. Kulin, and A. I. Frank. Eur. Phys. *J. D* **75,** 47 (2021).

Neutron reflection from a potential barrier moving with acceleration



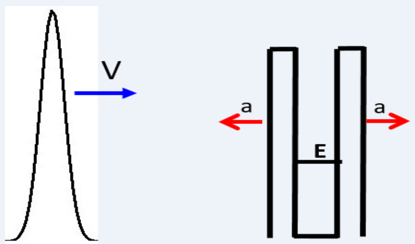


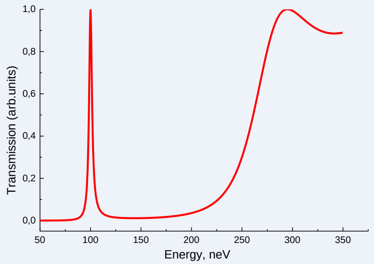


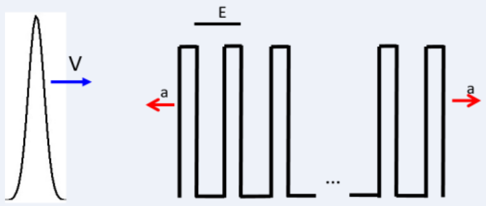


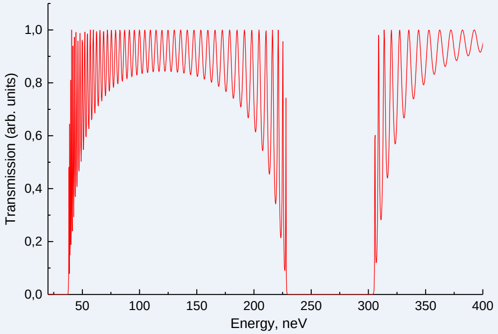
M. A. Zakharov, G. V. Kulin, and A. I. Frank. Eur. Phys. *J. D* **75,** 47 (2021).

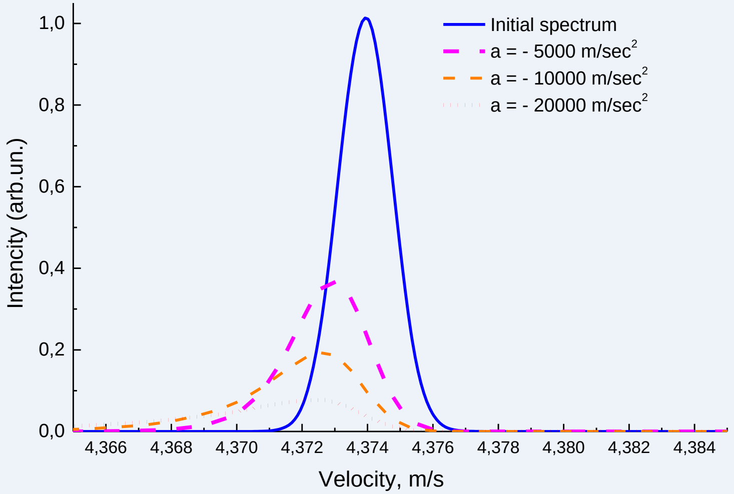
Tunneling of a neutron through a resonant potential structure moving with acceleration.

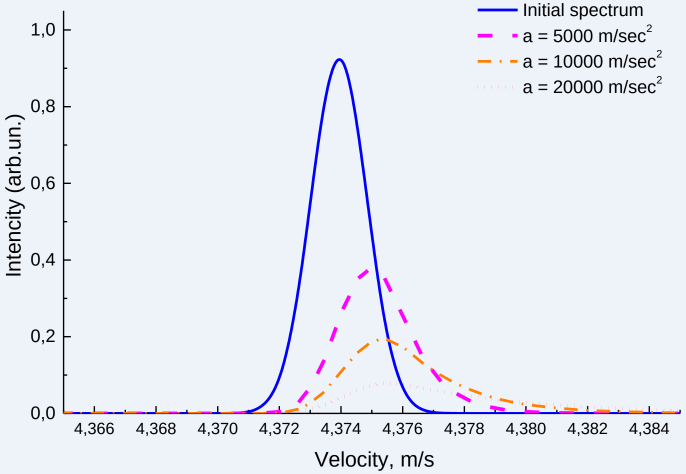




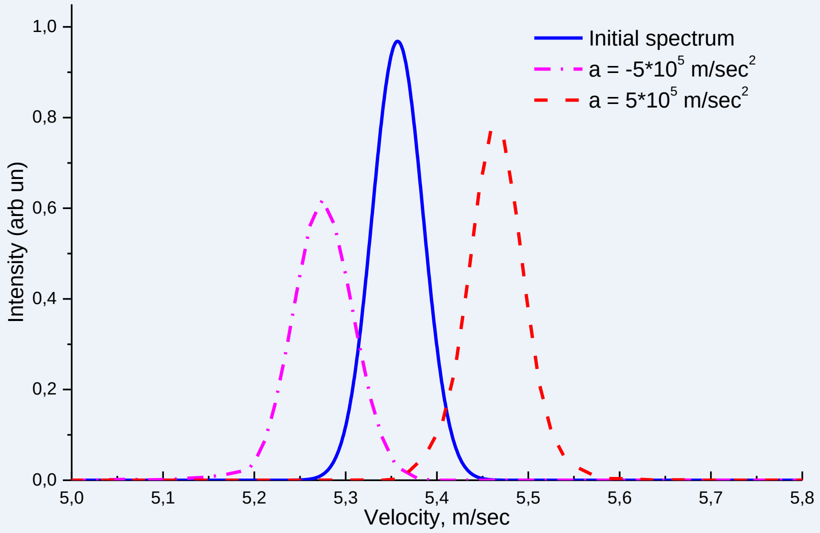








Fabry-Perot interferometer



M. A. Zakharov, G. V. Kulin, and A. I. Frank. Eur. Phys. *J. D* **75,** 47 (2021).

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

What follows from that for neutron optics ?

Group delay time at neutrons scattering by atomic nucleus

$$\psi(\mathbf{r})\Big|_{r>r_0} = e^{i\mathbf{k}_0\mathbf{r}} + f\,\frac{e^{ikr}}{r}$$

$$f = f' + if''$$

Scattering amplitude

σ_t - total cross-section

σ_s - scattering cross-section

σ_a - capture cross-section

GDT $\quad \tau = \hbar\dfrac{d\varphi}{dE}$

$$\sigma_t = \sigma_s + \sigma_a = \frac{4\pi}{k} f''$$

$$\sigma_s = 4\pi\left(f'\right)^2$$

$$\varphi = \frac{f''}{f'} = \frac{k\sigma_t\sqrt{4\pi}}{4\pi\sqrt{\sigma_s}} = \frac{k\left(\sigma_s + \sigma_a\right)}{\sqrt{4\pi\sigma_s}}$$

$$k\sigma_a = const$$

$$\tau = \hbar\frac{d\varphi}{dE} = \frac{1}{v}\sqrt{\frac{\sigma_s}{4\pi}}$$

$$\tau = \frac{|b|}{v}$$

For thermal neutrons $\quad \tau \approx 10^{-18}\,s$

For UCN $\quad \tau \approx 10^{-15}\,s$

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

Unsolved problems of the theory

$$\frac{\hbar}{\Delta\tau} >> \Delta(mv)^2$$

$$\Delta v = w\Delta\tau(?)$$

1. *The relationship we accepted between the change in velocity and GDT during scattering on an atomic nucleus is unlikely to be true for such shorts period of time. Should there be an Accelerating Effect in this case as well?*

2. *If there is an acceleration effect when scattering on an accelerating nucleus, then what is the effect of multiple scattering in the case of a medium?*

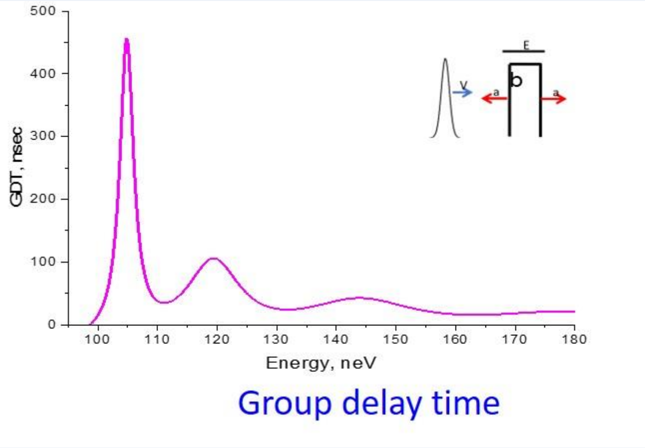
3. *The assumption of an inelastic and probably non-isotropic scattering pattern by an individual nucleus contradict the basic principles underlying the existing theory of neutron wave dispersion*

Apparently, neutron optics of accelerating media does not currently exist as a field of science, and the question of creating an appropriate theory turns out to be very relevant.

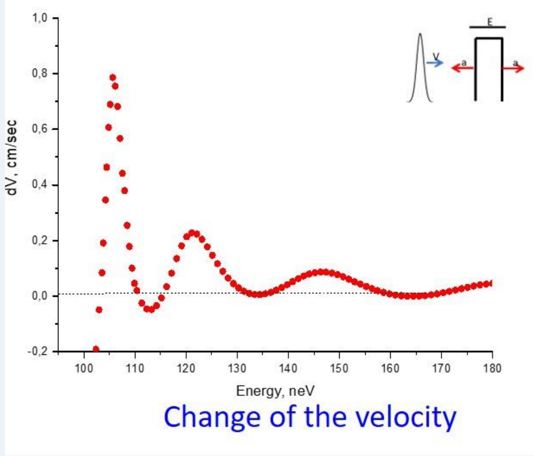
This is one of our tasks for the near future.

We are looking for the new experimental approaches

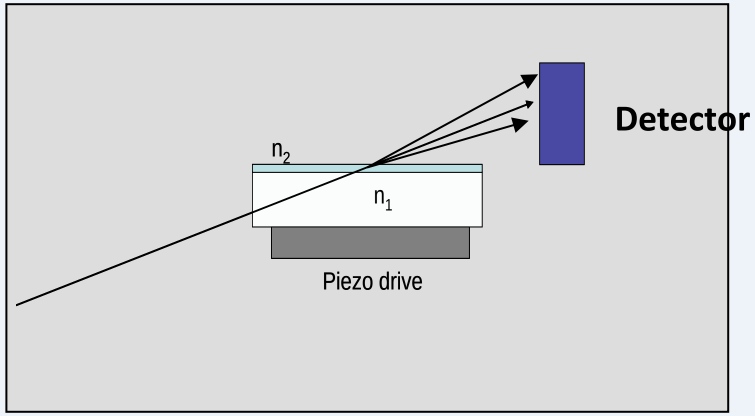
Neutron transmission above potential barrier



Group delay time

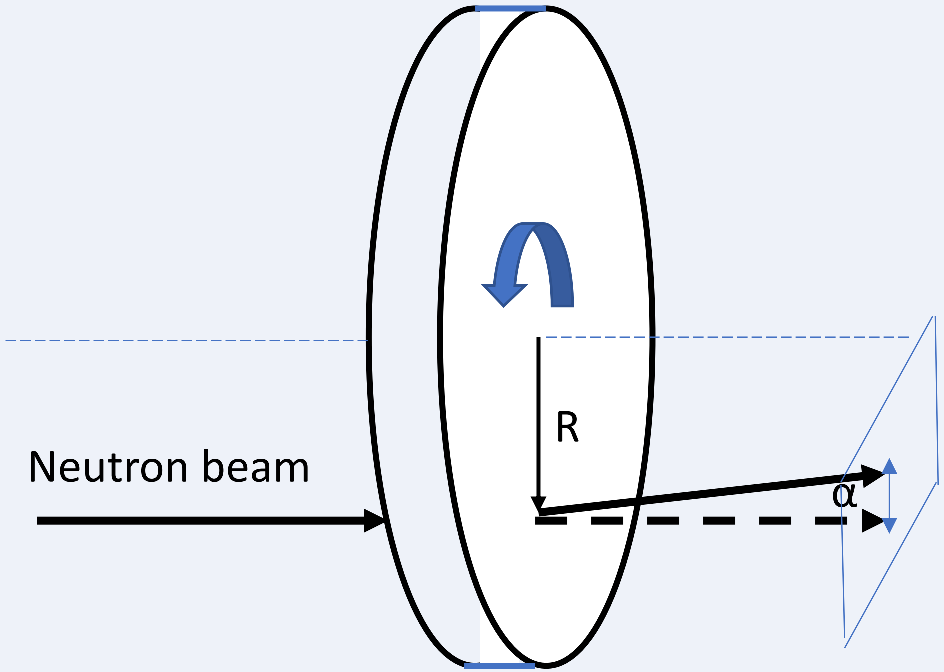


Change of the velocity



Acceleration of sample $2x10^5 \mathrm{m}/s^2$

Using centripetal acceleration. Easily achievable accelerations $10^5 \mathrm{m}/s^2$



Neutron diffraction by SAW for the test of the dispersion law in accelerating matter

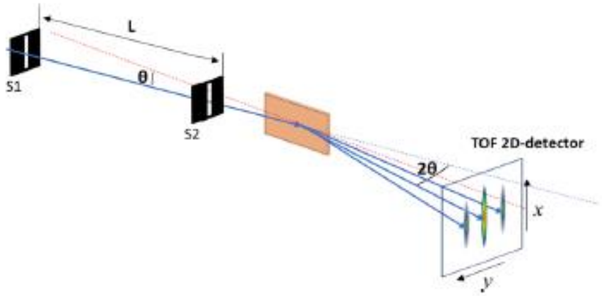


Fig. 1 Scheme of the experiment

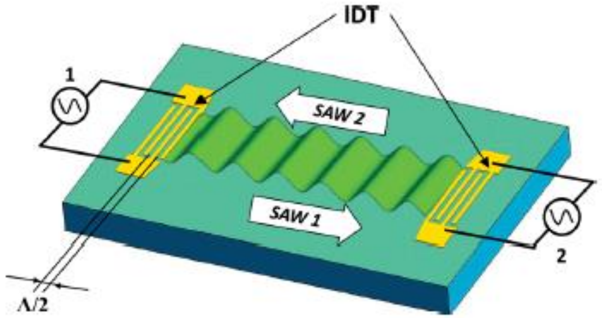
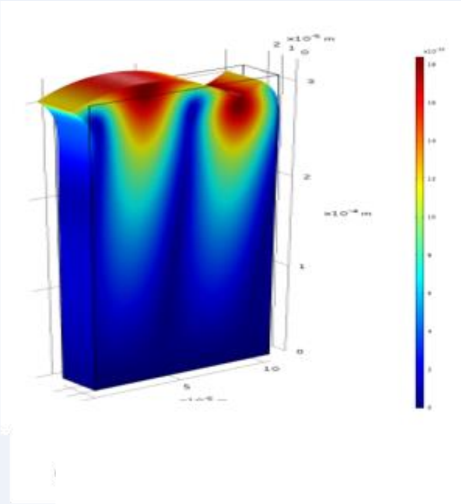
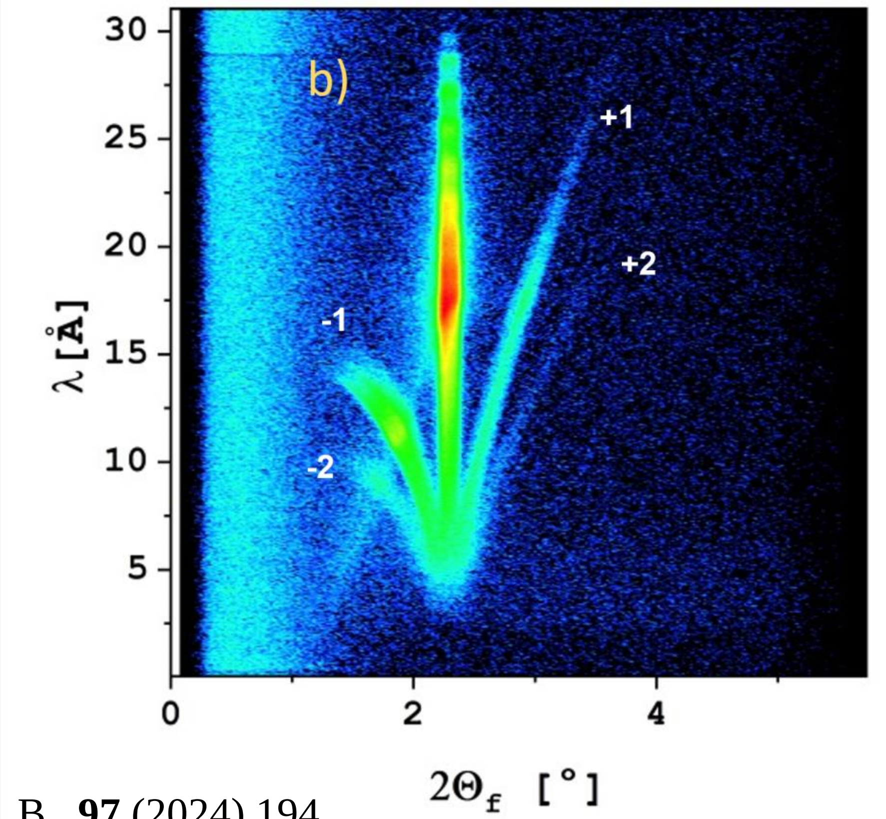


Fig. 2 The layout of sample with IDTs and the structure of the SAW formation, here Λ is a SAW wavelength

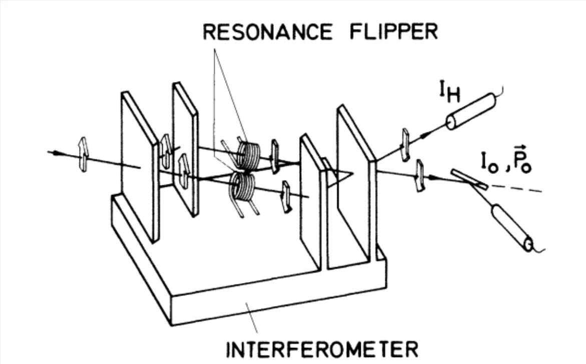
Acceleration of the surface and near-surface layer is up to $10^9 m/s^2$





G. V. Kulin, A. I.Frank, N.V.Rebrova et al. Eur. Phys. J. B , **97** (2024) 194

Acceleration effect in the case of birefringent and nonstationary spin precession



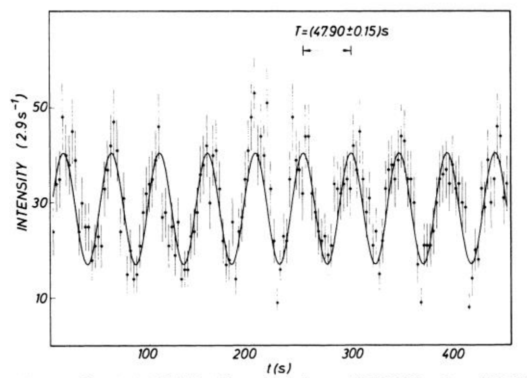
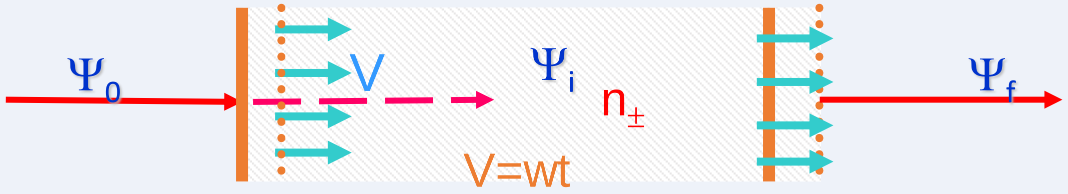


FIG. 6. (a) Real-time beat effect obtained if slightly different frequencies $\nu_{r1}=71.899\,80$ kHz and $\nu_{r2}=71.899\,78$ kHz ($\Delta\nu=0.02$ Hz) are applied to both rf coils. The observed beating period corresponds to an energy difference of the interfering beams of 8.6×10^{-17} eV and the energy resolution is determined as 2.7×10^{-19} eV. (b) The beat effect disappears completely if both coils are driven off resonance.

$$\Delta E \approx 10^{-16}\,\text{eV}$$

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



$$\Delta\omega_\pm = kw\Delta\tau_\pm \qquad \Delta\tau_\pm = \frac{d}{v}\left(\frac{1-n_\pm}{n_\pm}\right) \qquad \Delta E_\pm = \hbar\Delta\omega_\pm$$

$$\varphi(x,t) = (\Delta k_+ - \Delta k_-)x - (\Delta\omega_+ - \Delta\omega_-)t + \Delta\chi$$

In a fixed observation point and in neglecting by t dependence of $\Delta\chi$ spin rotation frequency Ω is

$$\varphi(t) = \Omega t \qquad \Omega = \frac{mwL}{\hbar}\left(\frac{n_+ - n_-}{n_+ n_-}\right)$$

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

Birefringence of the neutron waves (two samples)

1. Region with magnetic field or magnetic sample

$$n_\pm = \sqrt{1 \mp \frac{\mu B}{E}}$$

$$\Delta n \simeq \frac{\mu B}{E} \quad (\mu B \ll E)$$

$$\Omega = \frac{\mu B}{\hbar}\frac{mwd}{E} = \omega_L \frac{mwd}{2E}$$

$$\omega_L = \frac{2\mu B}{\hbar}$$

2. Polarized neutrons and polarized matter (nuclear pseudo magnetism)

V.G.Baryshevskii, M.I.Podgoretsky. JETP 47 (1964) 1050.
A.Abragam, et al., Phys.Rev.Lett, 31 (1973) 776.

$$n_\pm = \left(1 \mp \frac{U_\pm}{E}\right)^{1/2}$$

$$U_\pm = \frac{2\pi\hbar^2}{m}\rho b_\pm$$

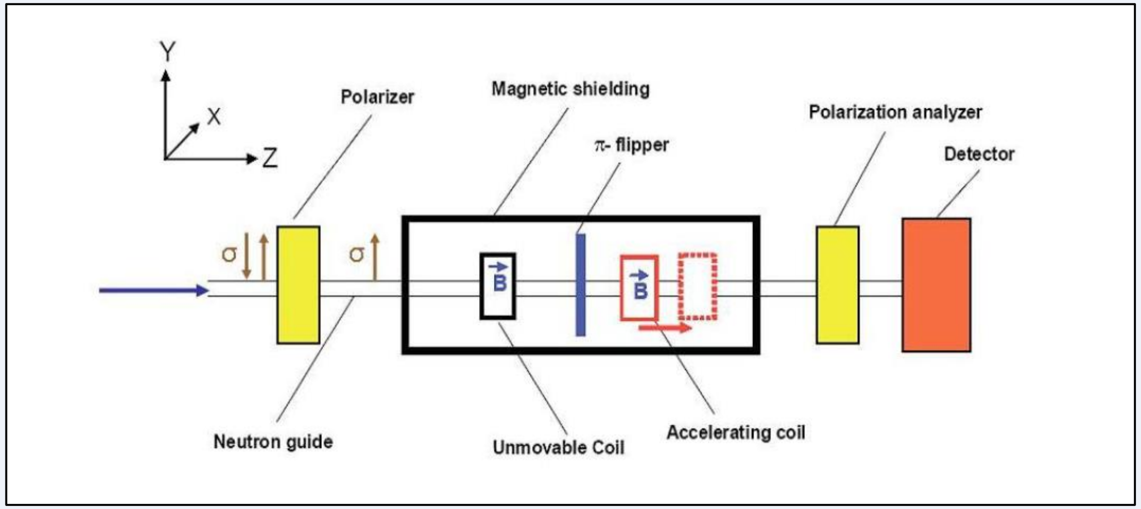
$$b_\pm \rightarrow J = I \pm 1/2$$

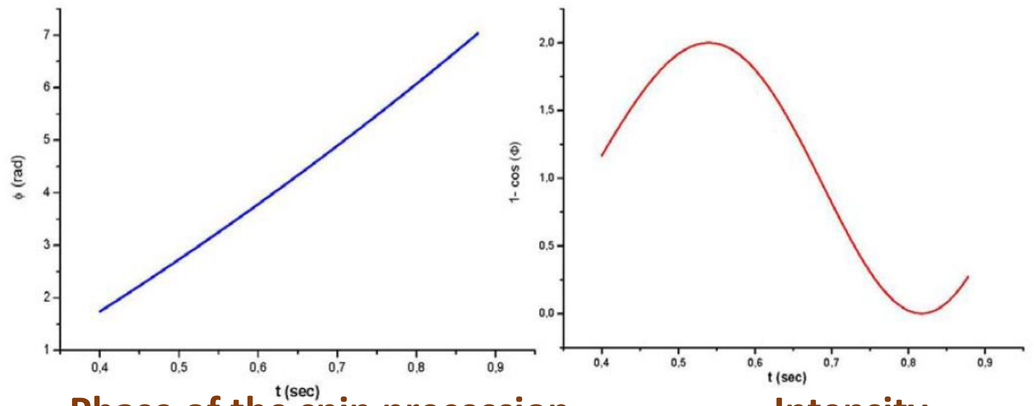
$$\Omega = p_{nuc}\frac{mwd}{\hbar}\frac{\bar{U}}{n^2 2E}\frac{\Delta b}{b}$$

For UCN, w=10g and d=1mm

$$\Omega = p_{nuc}\frac{\Delta b}{b}\times 10^6$$

Possibility of the experimental observation (birefringence in the magnetic field)





Phase of the spin precession **Intensity**

A.I.Frank. Journal of Physics: Conf. Ser. **711** (2016) 012016.

UCN
B=1 Gauss
$n_{\pm} = 1 \pm 2.8\times10^{-5}$
d =1cm
a = 50cm/s^2, T = 0.5s
S = 10cm
V_{max} = 24.5 cm/s

$\Omega \approx$ 4.2 rad/s

$$\Delta E = \pm\hbar\Omega / 2 \approx \pm 1.5\times10^{-15}\,\text{eV}$$

Conclusion

Any object that scatters a wave or receives and then emits a signal shifts frequency of the wave if it is moving with acceleration

This conclusion is also true for quantum objects

We can talk about the Acceleration Effect as a general effect that complements the Doppler effect but differs from it in that the frequency shift is determined not by the speed of the object but by its acceleration.

It can be assumed that the acceleration effect should also take place in the case of neutron scattering on atomic nuclei of accelerating matter. This assumption raises a number of new questions for the theory

Some approaches to the possible future experiments are discussed

Many thanks to my colleagues

S.V. Gorunov, M.A.Zakharov, G,V.Kulin, D.V. Kustov.

V.A. Naumov

A.N. Strepetov

P. Geltenbort, M. Jentschel, T. Jenke, P. Gutfreund

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Thank you for your attention!