The Acceleration Effect in Quantum mechanics And Neutron Optics

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Outline

- Prehistory
- Interaction of waves with an accelerating medium (elementary theory)
- Experimental observation of the Acceleration Matter Effect
- AME and the equivalence principle
- Generalization of the AME – Acceleration Effect as a general physical phenomenon
- Macroscopic effect
- Acceleration Effect and quantum mechanics
- Unsolved problems of the theory and possible experimental approaches
- Conclusion

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Transmission of electromagnetic waves throw a dielectric slab moving with acceleration. K. Tanaka, 1982

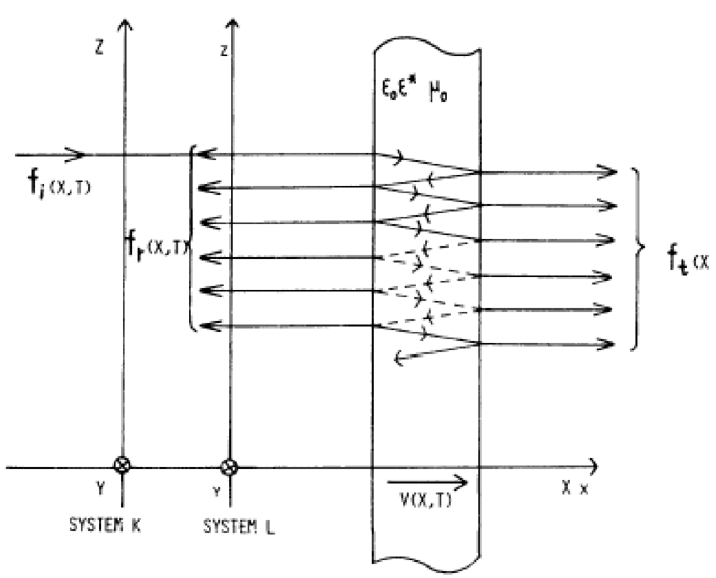


FIG. 1. Geometry of the problem.

PHYSICAL REVIEW A VOLUME 25, NUMBER 1 JANUARY 1982

Reflection and transmission of electromagnetic waves by a linearly accelerated dielectric slab

Kazuo Tanaka
Department of Electrical Engineering, Gifu Univeristy, Gifu City, Gifu 501-11, Japan

(Received 16 March 1981)

The reflection and transmission of electromagnetic waves by a dielectric slab which performs a given accelerated motion is investigated theoretically. Rigorous expressions for the reflected and transmitted waves are obtained by making use of the covariant properties of Maxwell's equations under the arbitrary coordinate transformations. It is found that there exists a small Doppler shift in frequency for the transmitted wave due to the drag effect of the moving medium. It is shown that this frequency shift depends on the acceleration, the index of refraction, and the width of the slab and is independent of the velocity of the slab.

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

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

Amazing result!

The work remained practically unknown for a long time.

F.W. Kowalsky. 1993

Physics Letters A 182 (1993) 335–340
North-Holland

Interaction of neutrons with accelerating matter: test of the equivalence principle

F.V. Kowalski
Department of Physics, Colorado School of Mines, Golden, CO 80401, USA

Received 20 August 1993; accepted for publication 22 September 1993
Communicated by J.P. Vigier

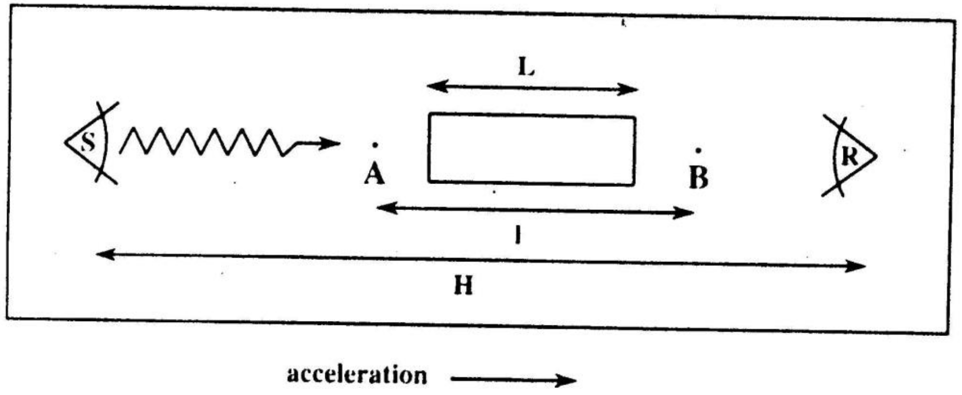


Fig. 1. The source, S, emits a neutron which propagates through the slab of material to the receiver, R. The slab, S, and R all accelerate rigidly with constant acceleration *g* in the direction shown. Points A and B are fixed in the inertial frame discussed in the text.

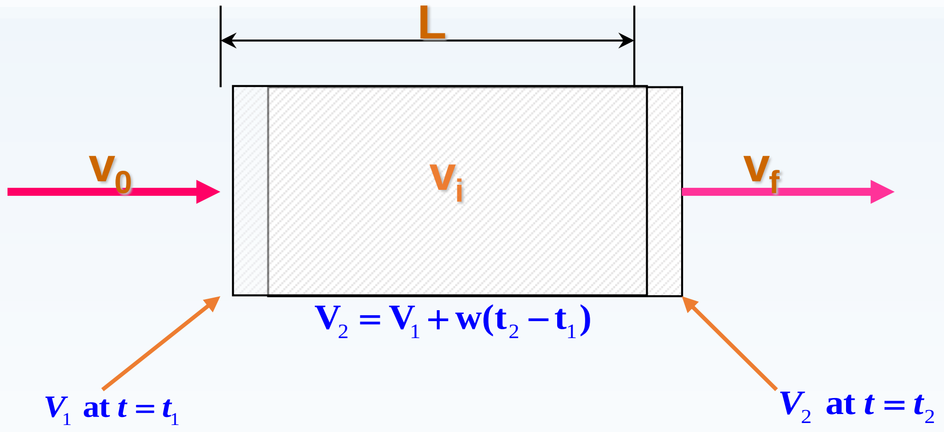
A thought experiment to test the principle of equivalence – the identity of the results in an inertial system in the presence of gravity and in a non-inertial system.

Inertia and gravity are indistinguishable

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

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

A quasi-classical approach to the derivation of the Kowalski formula and the proposal of a possible experiment (*V.G. Nosov & A.I.Frank,1998*)



Assumptions:

1) Effective optical potential model is also valid in the case of accelerating matter
2) Quasi – classical approach is correct

$$U = \frac{2\pi\hbar^2}{m}\rho b$$

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

$$n^2 = 1 - 4\pi\rho b \qquad V = nV_0$$

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

V.G.Nosov, A.I.Frank. Physics of Atomic Nuclei, 61, 613, 1998

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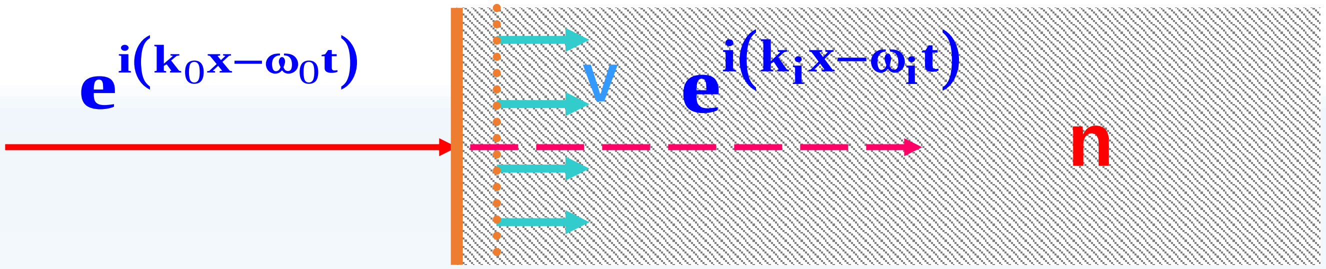
Refraction of a wave at the border of the moving matter



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

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

Doppler shift at refraction

Massive particle (neutron)

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

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

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

Light

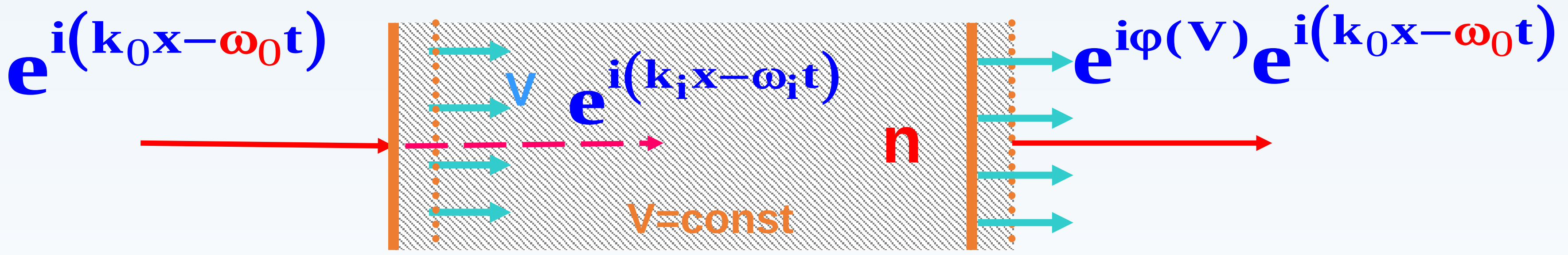
C. Yeh. J. Appl. Phys. **36**, 3513 (1965)

$$k_0 = \frac{\omega_0}{c} \qquad \left(\frac{v}{c} \ll 1\right)$$

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

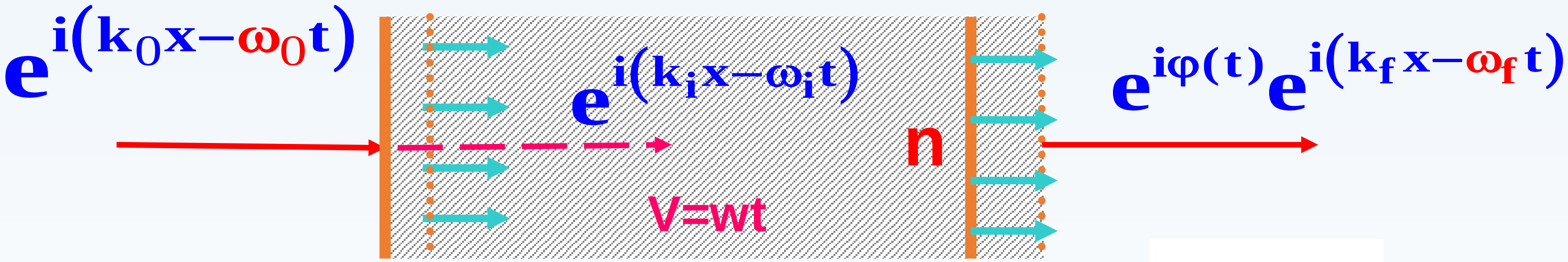
Fresnel drag

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)



$\omega_f \neq \omega_0$

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

Differential Doppler effect and Accelerating Matter Effect in neutron optics

$$\omega_i = \omega_0 + (n'-1)k_0V \qquad (V \ll v_0)$$

$$\Delta\omega = (n'-1)k_0V - (n'-1)k_0(V + w\Delta t) = k_0 w(1-n')\Delta t$$

$$\Delta t = \frac{d}{n'v_0}$$

$$\Delta\omega \cong wd\frac{1-n}{n}\frac{k_0}{v_0} = \frac{mwd}{\hbar}\frac{1-n}{n} \qquad (V,\ wt \ll v_0)$$

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

Kowalski-Nosov-Frank

Assumptions:

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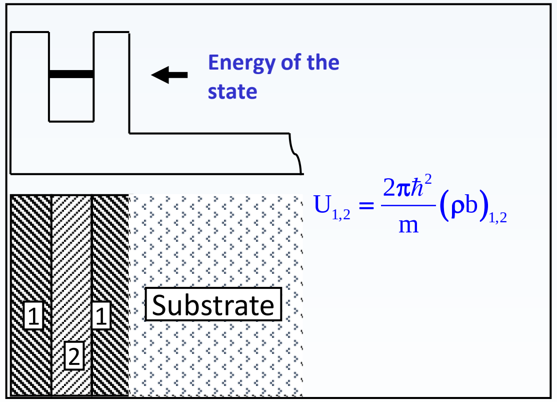
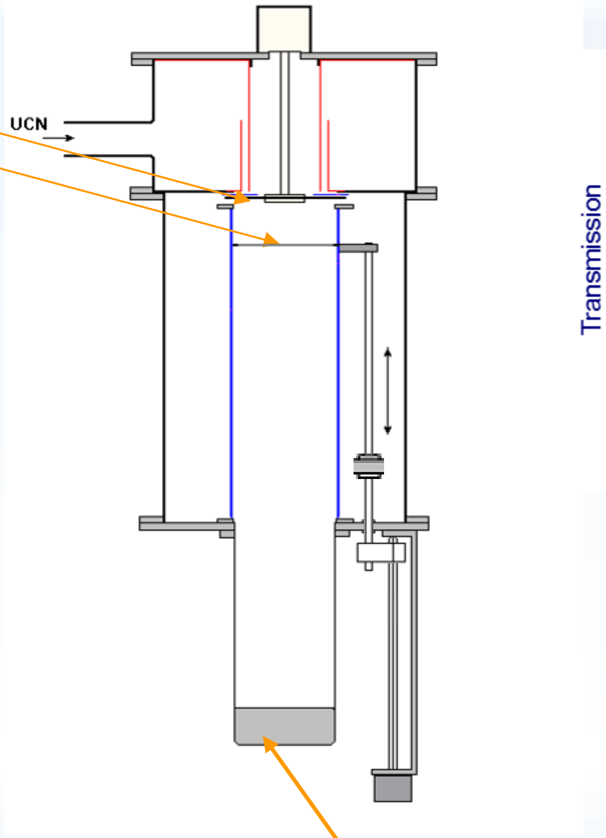
UCN spectrometry with Fabry-Perot interferometers

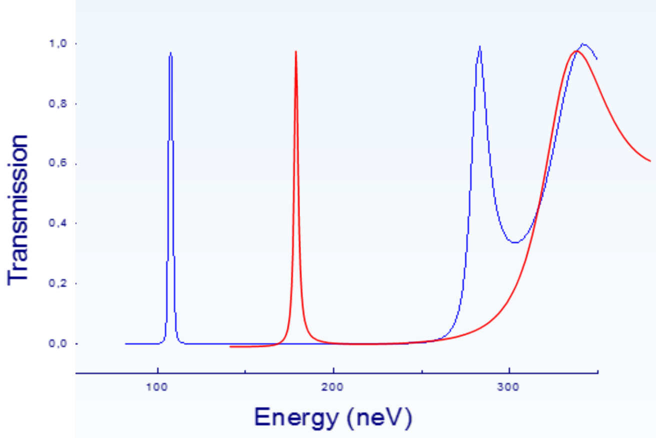
mg=1.02 neV/cm

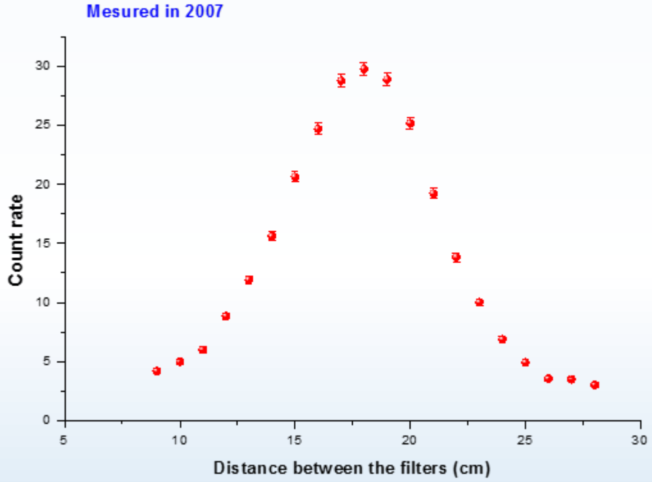
Two IFP with variable space between them



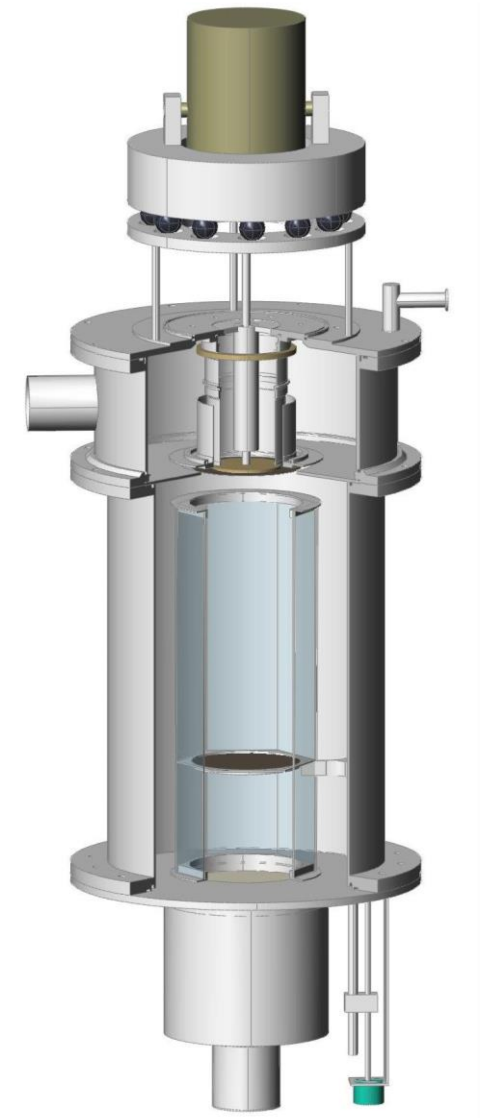


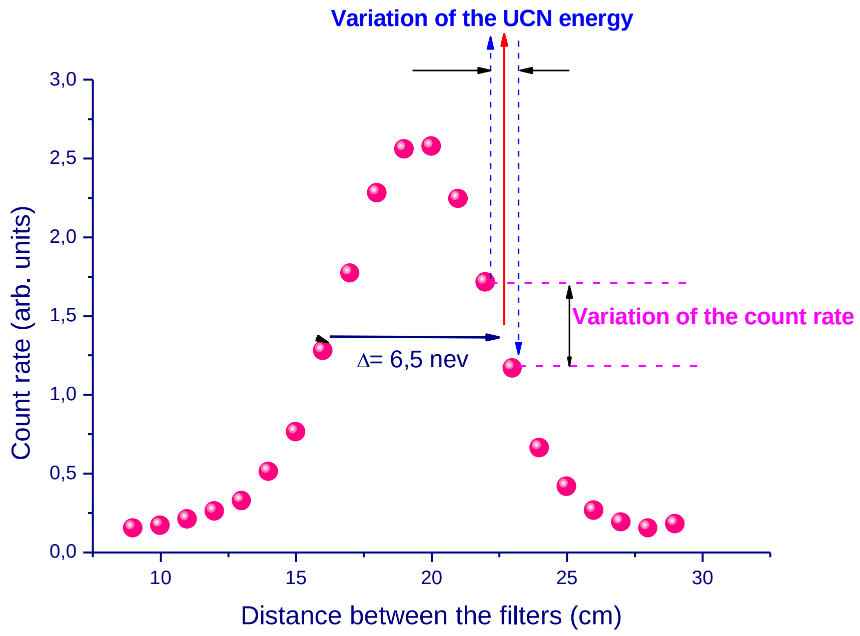
Detector

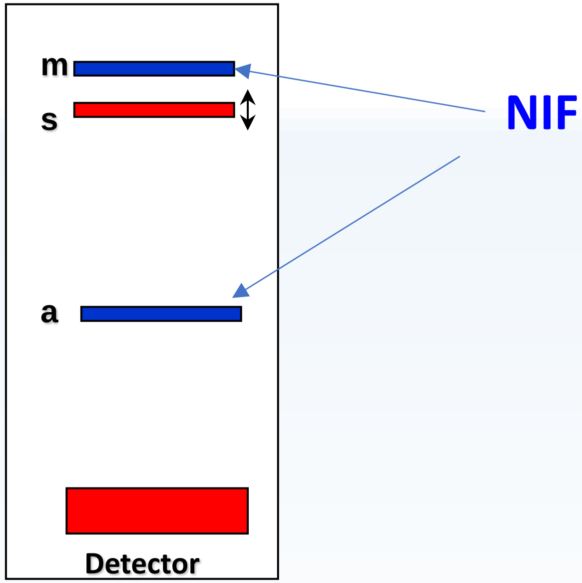




The principle of the AME experimental observation as it was proposed in 1998



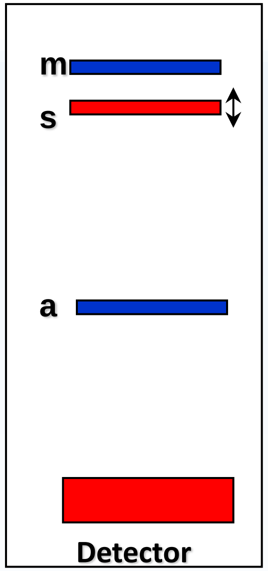


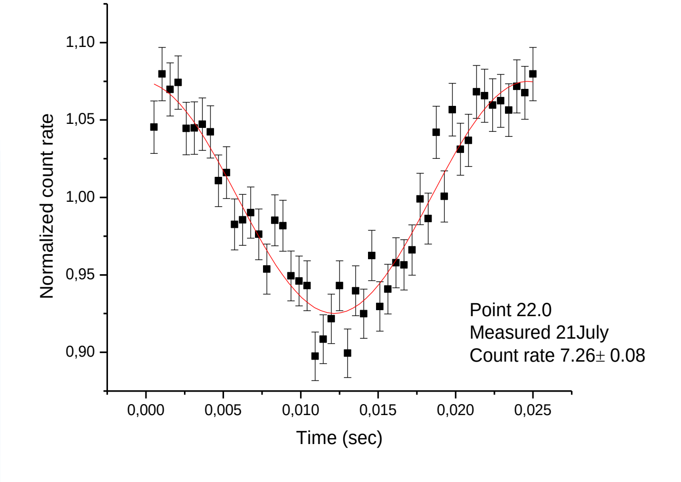


$\Delta E \approx (2\text{-}5)\times 10^{-10}$ eV

Periodically 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

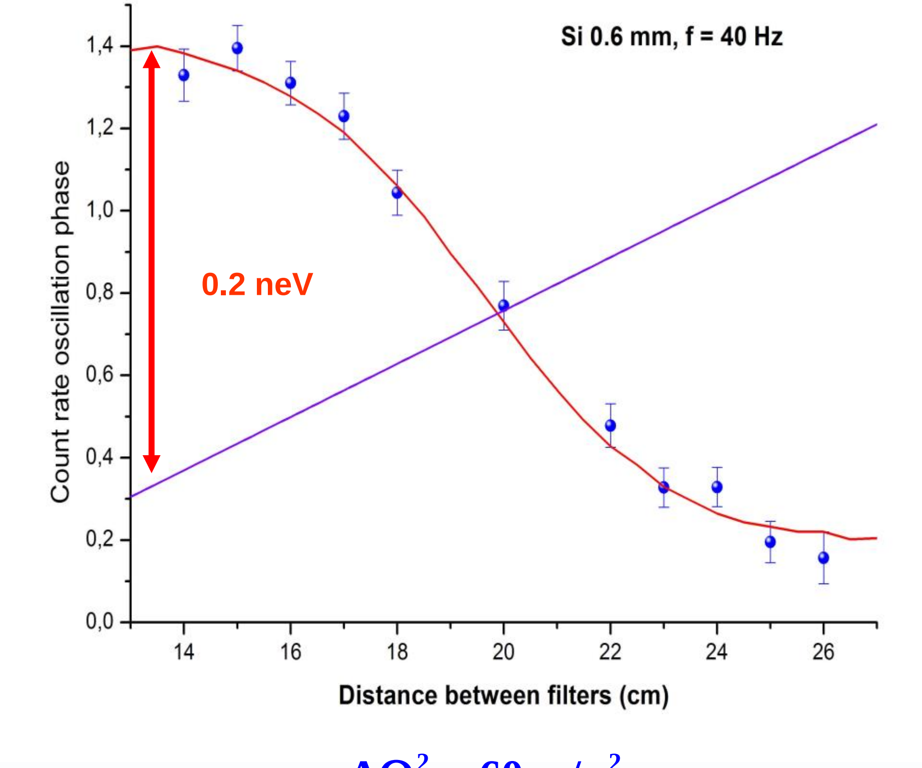




$a \cong -A\Omega^2 \sin\Omega t$ $V \cong A\Omega \cos\Omega t$

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

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



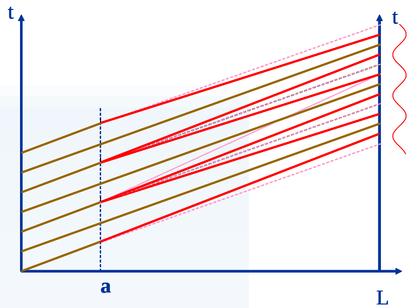
$$w_{max} = A\Omega^2 \approx 60 m/s^2$$

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

$$K = 0.94 \pm 0.06$$

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

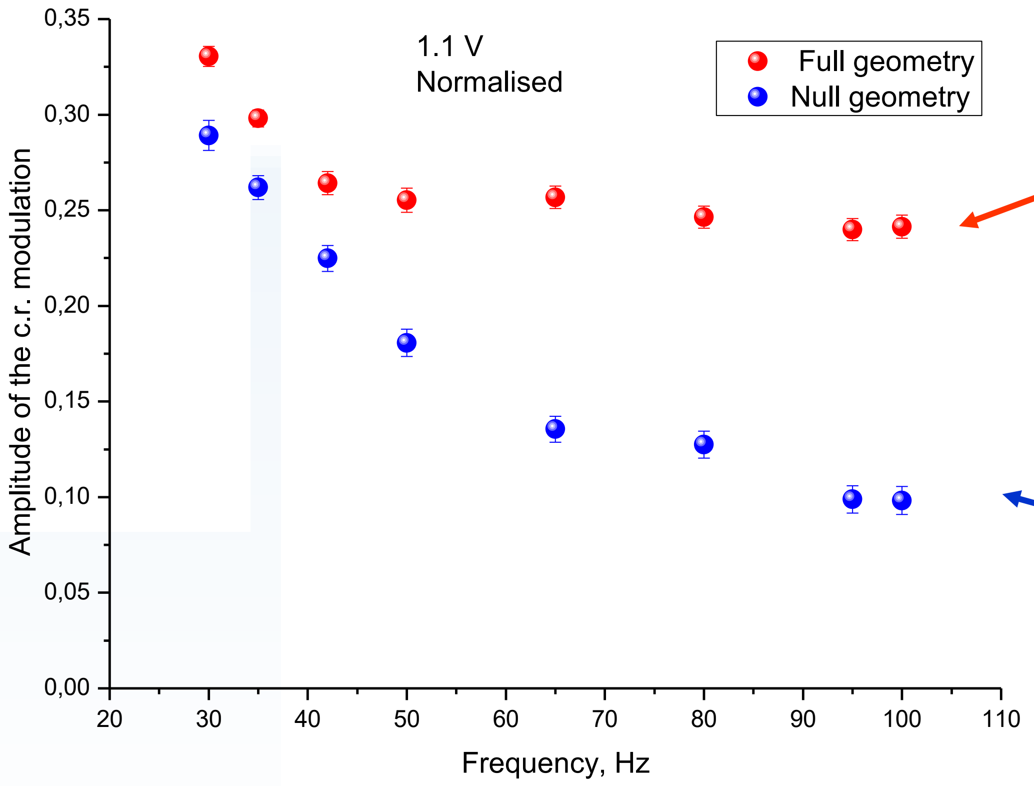
Observation of the weak time focusing due to AME

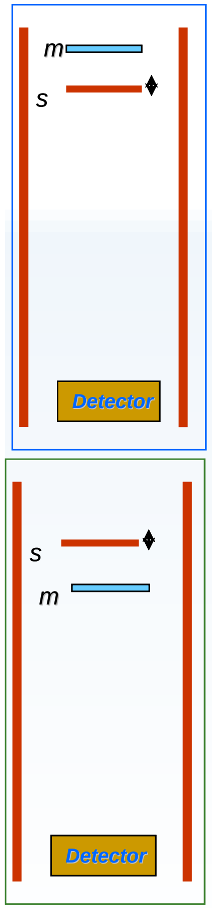


$$w \cong -A\Omega^2 \sin\Omega t$$

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

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





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)

Diffraction experiment of the PNPI group

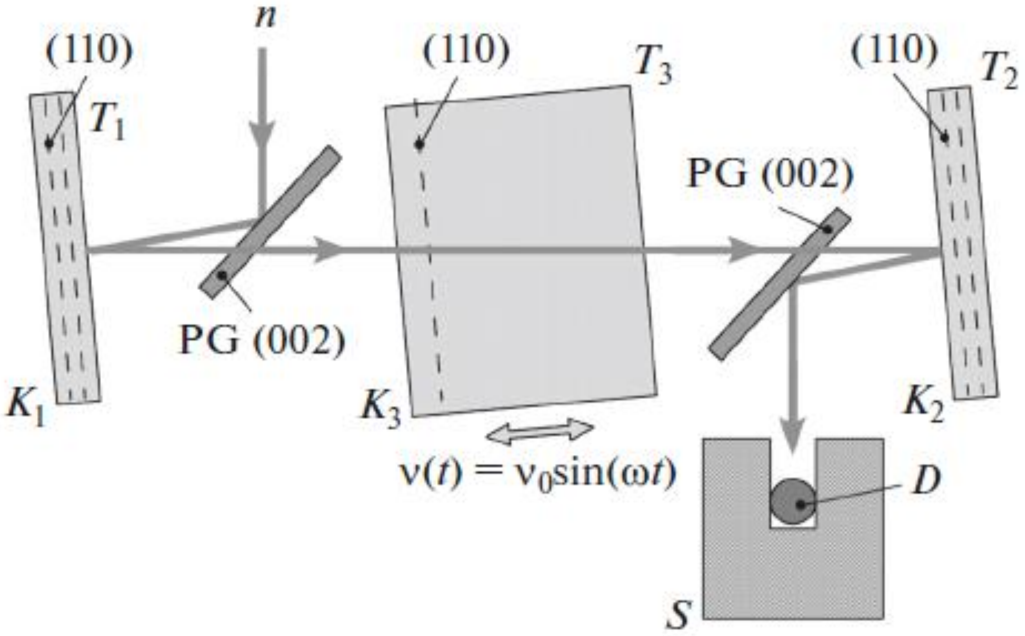


Fig. 1. Scheme of experimental setup: (n) collimated neutron beam, (K_{1-3}) quartz single crystals of temperature T_{1-3}, (PG) pyrolytic-graphite crystals, (D) neutron detector, and (S) detector shield.

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

But interpretation of the effect is debatable

The observed effect can be explained in the framework of differential Doppler shift at the boundary of a moving substance

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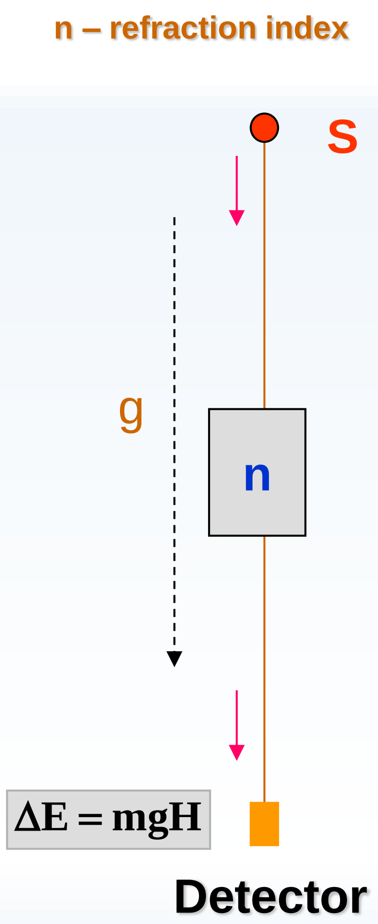
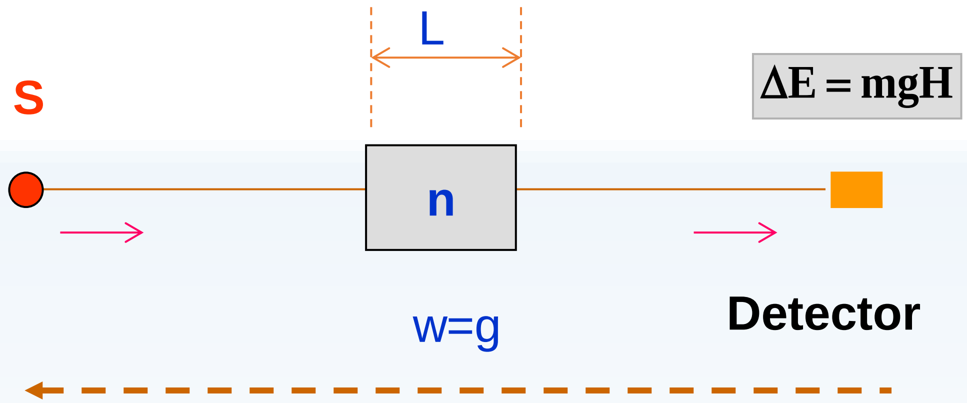
Accelerating sample and the equivalence principle



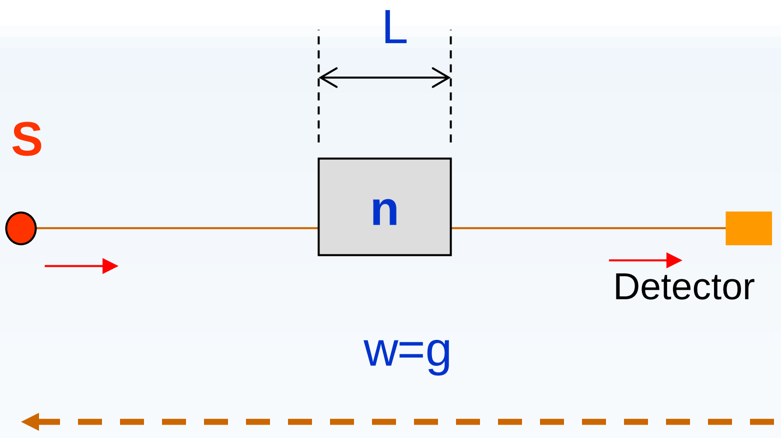


1. **In both cases the energy, measured by the detector, must be the same due to the equivalence principle**
2. **Introduction of the refracting slab does not change the energy due to the energy conservation law (see left fig.)**
3. **Delay time due to refraction is $\Delta\tau$**

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

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 time delay $\Delta\tau$ is the only effect related with sample, then introducing of (accelerating) sample would result in change of detected energy what contradicts 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

Accelerating Matter Effect in neutron and light optics

Neutrons

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

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

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

KNF formula

Si $L \approx 0.6$ *mm,*
$w \approx 10$ *g*

$$\frac{\Delta E}{E} \approx 3 \times 10^{-3}$$

Light and relativistic parrticle

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

$$\Delta\omega \approx \omega\frac{\Delta v}{c} = \omega\frac{w\Delta\tau}{c}$$

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

Tanaka formula

Glass
$L \approx 1$*m,* $w \approx 10$ *g*

$$\frac{\Delta\omega}{\omega} = 5 \times 10^{-15}$$

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The Accelerating Matter effect (AME) was predicted for light, neutrons and neutrinos, but was observed only for neutrons.

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

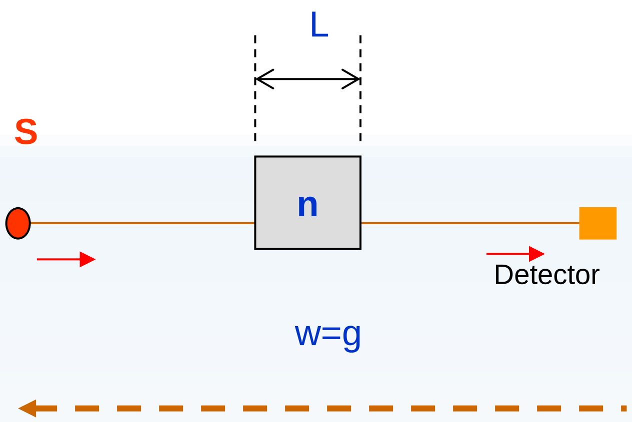
A.I. Frank, P.Geltenbort, G.V.Kulin, et al, Phys. At. Nuclei, 71 (2008) 1656.

Experiment of V.V. Voronin et al. (2014) demonstrated the validity of this concept for the case when the difference between wave numbers in a vacuum and in a substance is due not to refraction but to diffraction

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

But is it really just an optical effect?

Once again concerning the accelerating sample and the equivalence principle



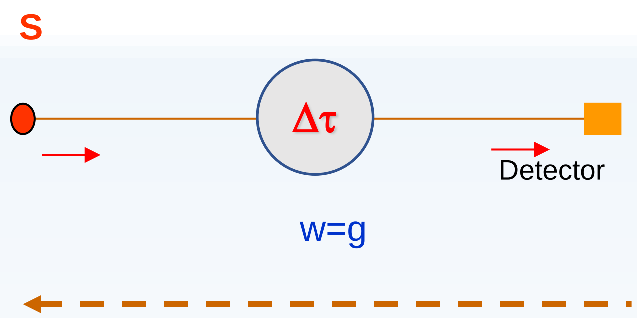
$$\Delta v = w\Delta\tau$$

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

We have previously concluded that in order for the equivalence principle to hold, the time delay $\Delta\tau$ resulting due to the difference in wave vectors in vacuum and sample must be accompanied by a change in energy

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

Once again concerning the accelerating sample and the equivalence principle



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

Any interaction is necessary 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. *Interaction of a wave with an accelerating object and the equivalence principle*. Physics-Uspeckhi, 63, 500-502 (2020)

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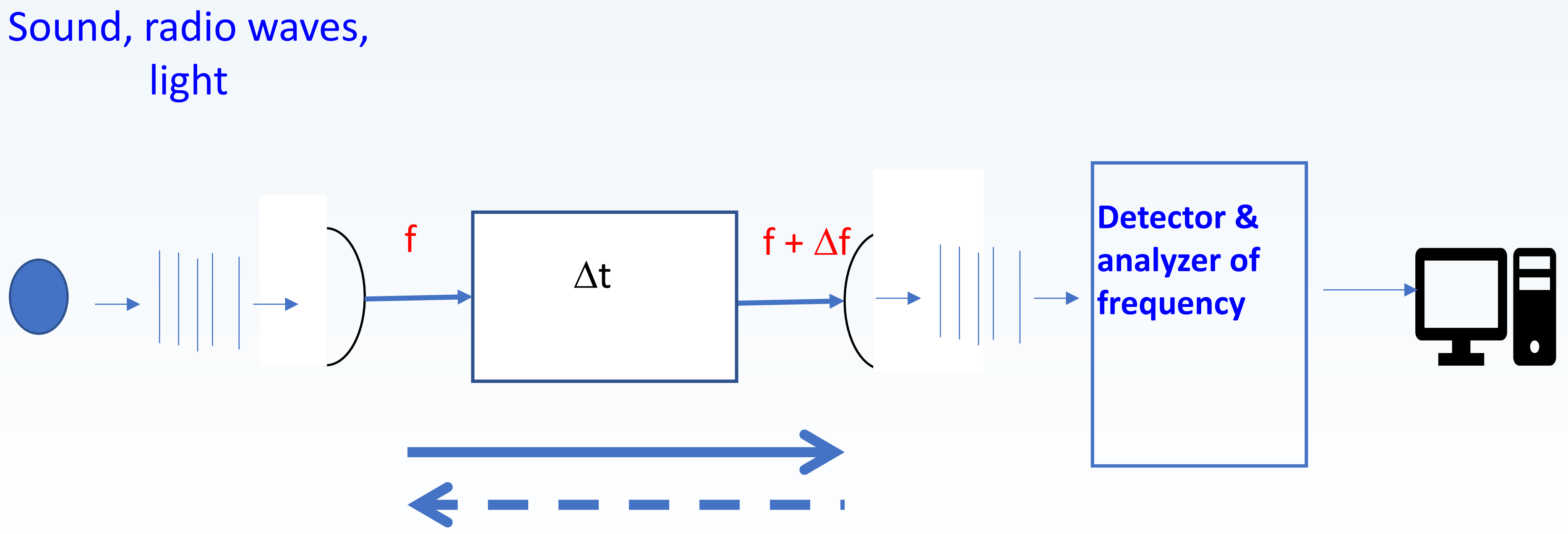
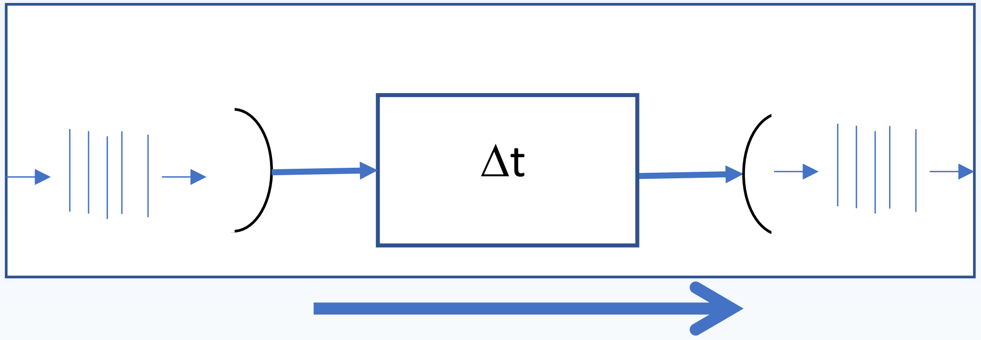
The frequency of the wave, emitted by a transceiver moving with acceleration, differs from an initial one



$$V = wt$$

The acceleration effect and Doppler effect

In many cases, the acceleration effect can 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.



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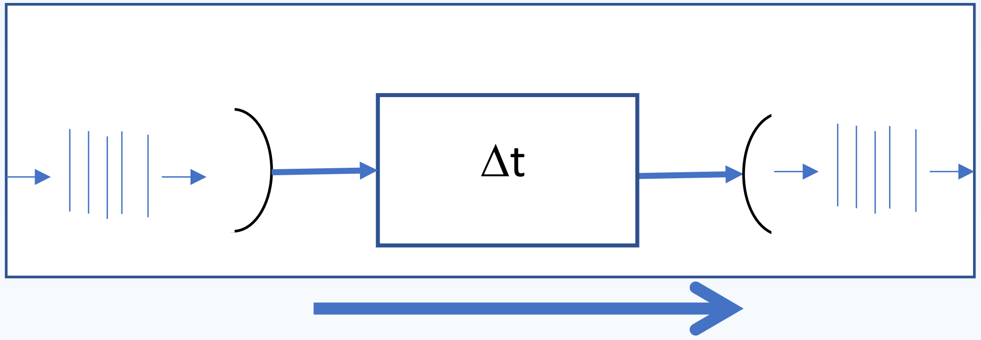

$$V = wt$$

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

And if this is true, what should be taken as a measure of time delay?

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).

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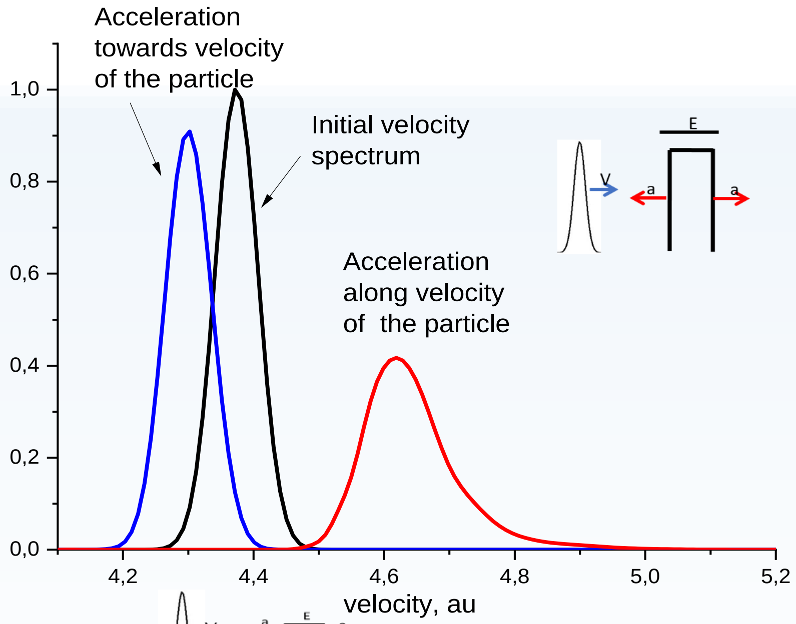
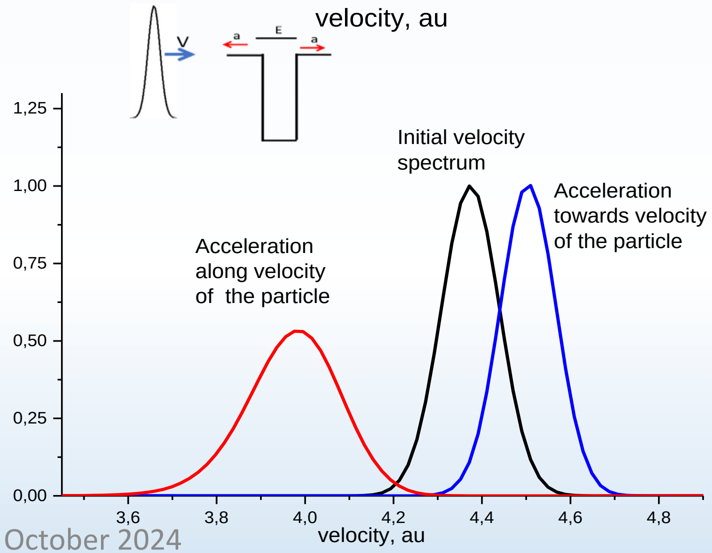
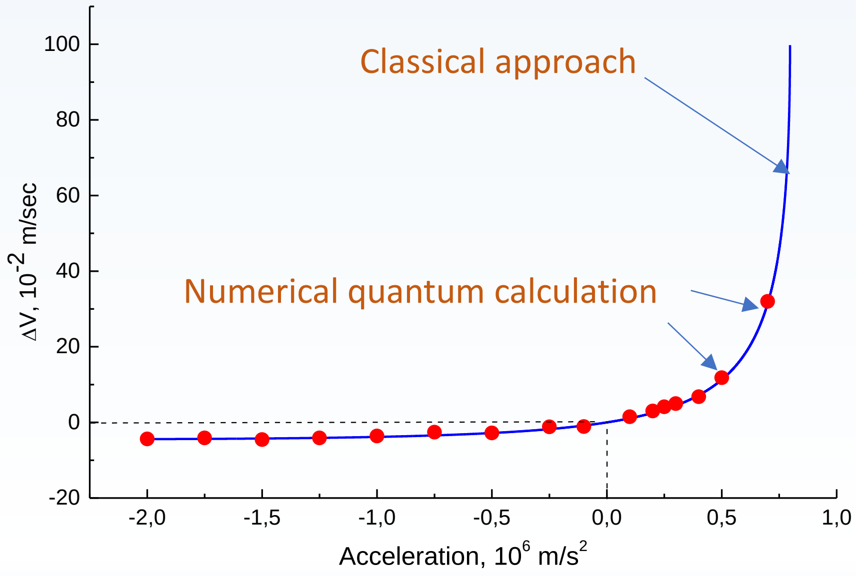
Numerical calculations based on the method of the evolution operator splitting

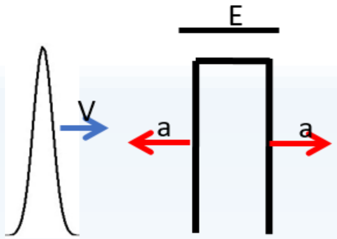
The Acceleration Effect when a wave packet (neutron) passes through a potential structure moving with acceleration. The case of a potential barrier and wheel

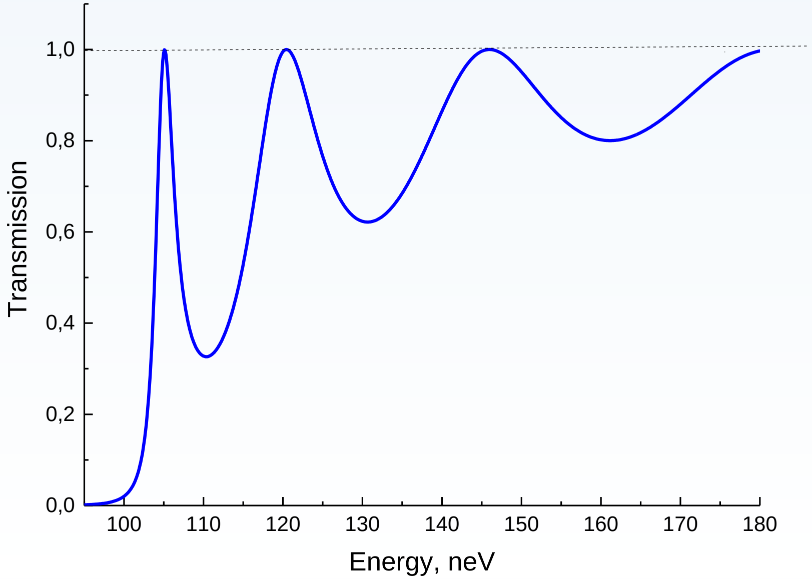


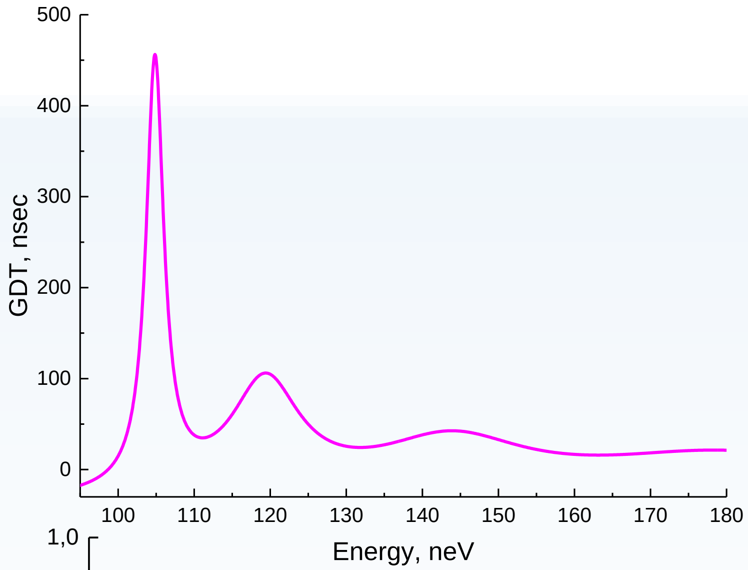




The Acceleration Effect when a neutron passes through a potential structure moving with acceleration. Under the barrier passage. The interference effects are significant.

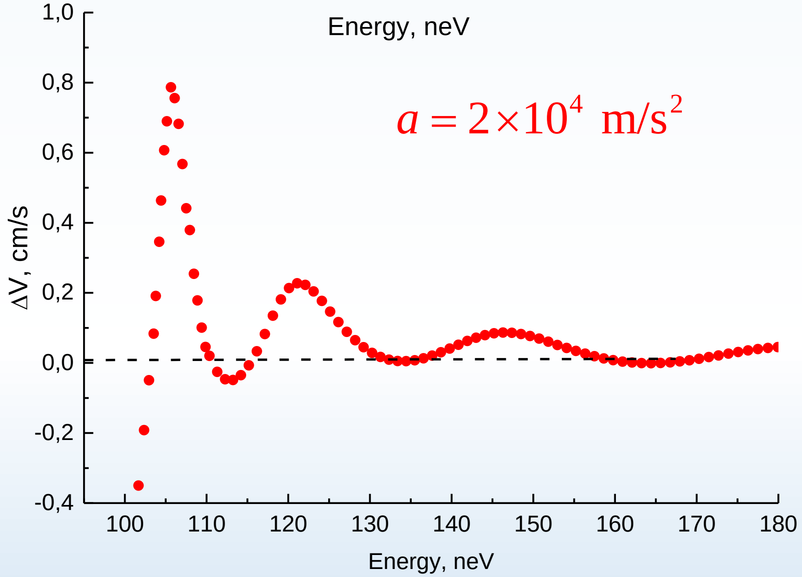






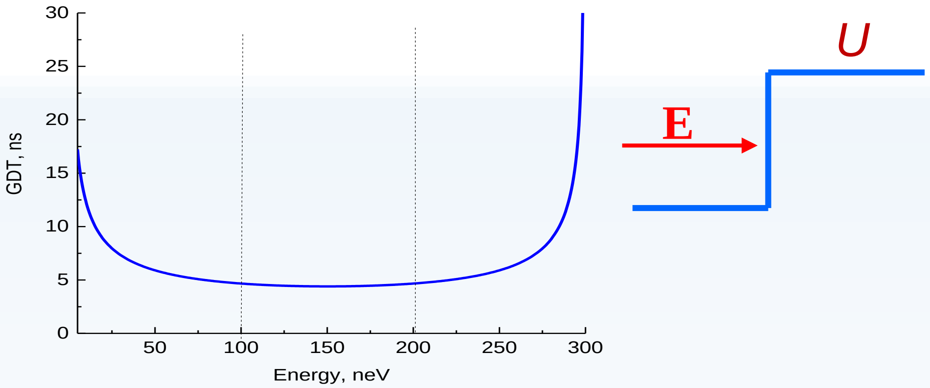
$$\tau_g = \hbar\left(\frac{d\varphi}{dE_z}\right)$$

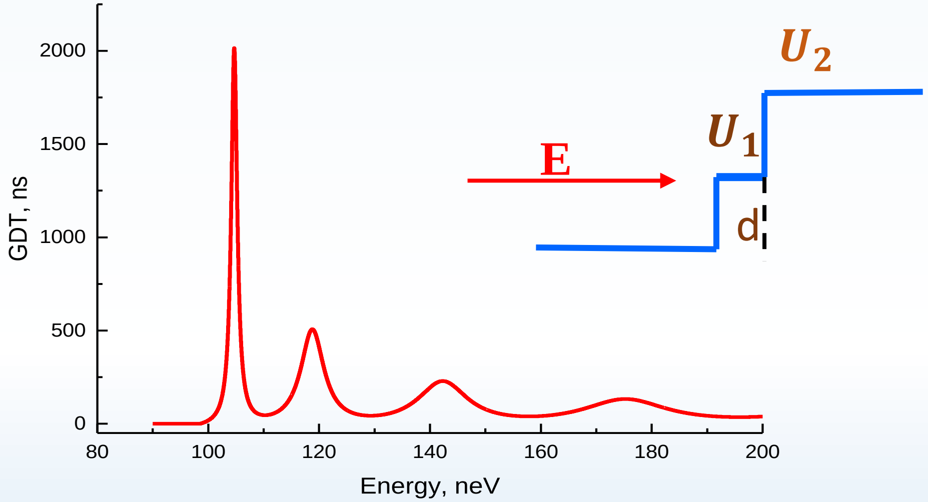
Group delay time (GDT)

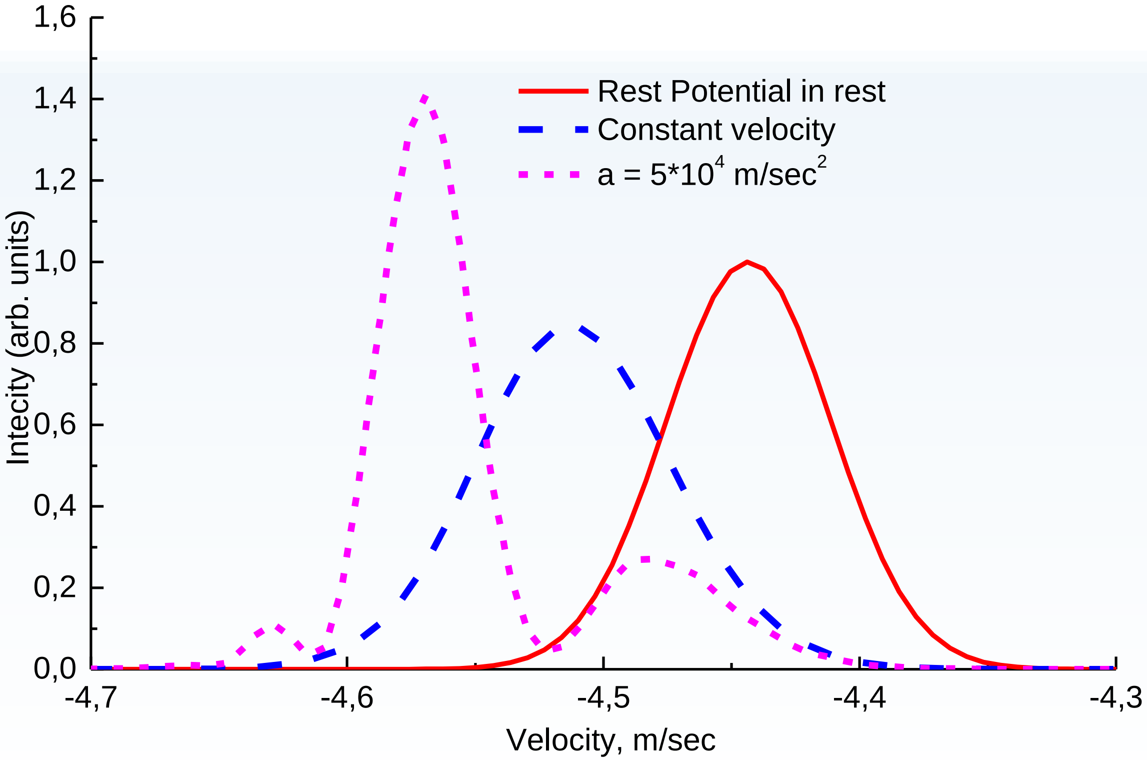


$$\Delta v \approx w\tau$$

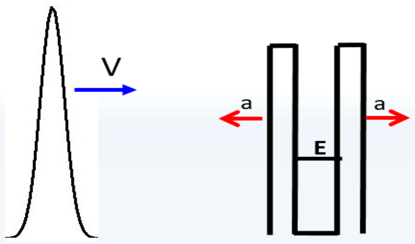
Neutron reflection from a potential barrier moving with acceleration

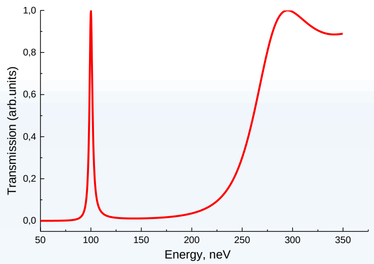


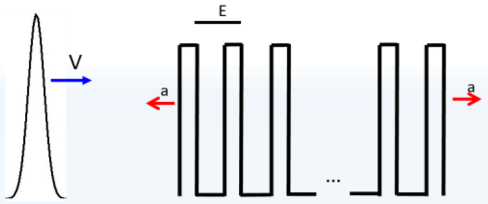


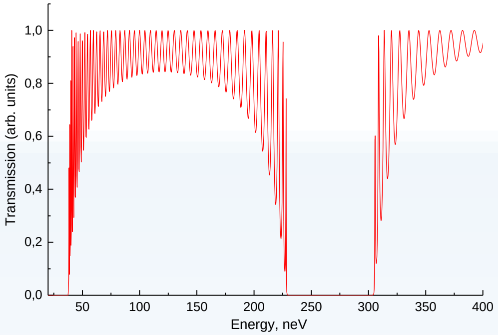


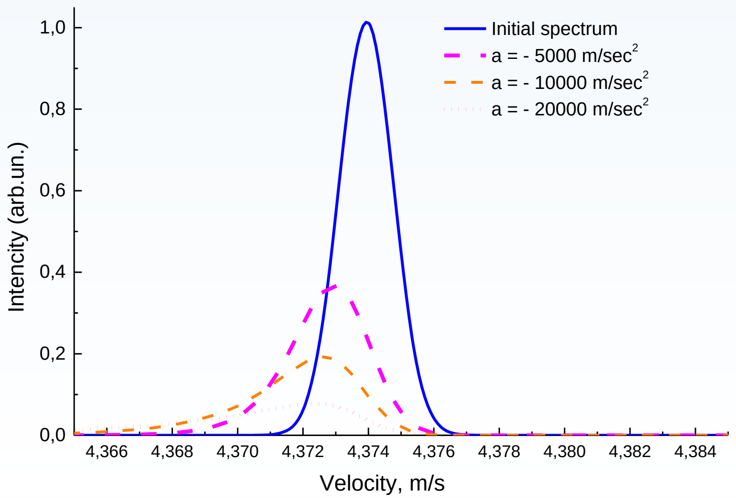
Tunneling of a neutron through a resonant potential structure moving with acceleration.

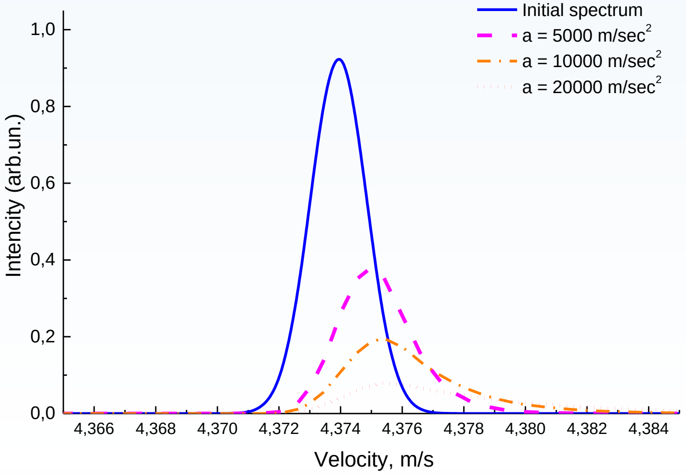


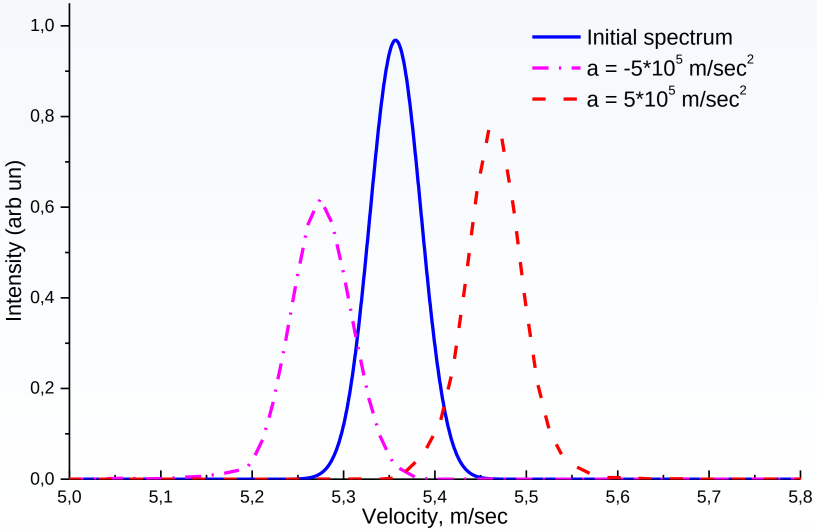












Fabry-Perot interferometer

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

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

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

What follows from that for neutron optics ?

- Prehistory
- Interaction of waves with an accelerating medium (elementary theory)
- Experimental observation of the Acceleration Matter Effect
- AME and the equivalence principle
- Generalization of the AME – Acceleration Effect as a general physical phenomenon
- Macroscopic effect
- Acceleration Effect and quantum mechanics
- **Unsolved problems of the theory and possible experimental approaches**
- Conclusion

Group delay time at neutrons scattering by atomic nucleus

$$\psi(\mathbf{r})\Big|_{r>r_0} = e^{ik_0 r} + f\frac{e^{ikr}}{r}$$

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

Scattering amplitude

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

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

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

σ_t - total cross-section

σ_s - scattering cross-section

σ_a - capture cross-section

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

$$k\sigma_a = const$$

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

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

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

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

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

Unsolved problems of the theory

1. *The ratio we have adopted for the relationship between velocity changes and GDT during scattering on an atomic nucleus is hardly correct for such short periods of times. Should the acceleration effect exist in this case as well, and how to evaluate it?*

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

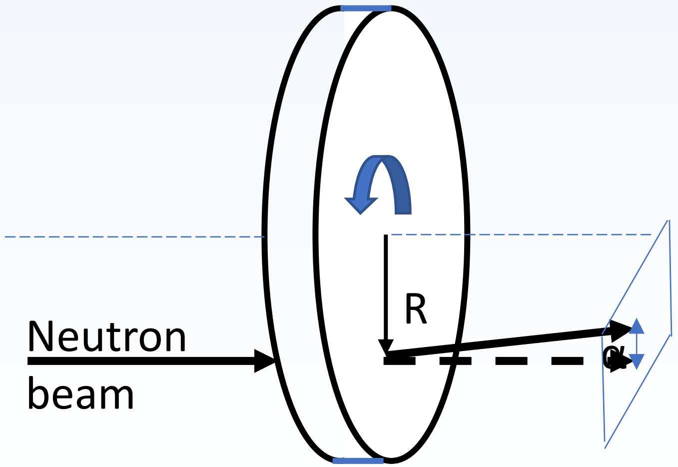
$$\Delta v = w\Delta\tau(?)$$

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?*

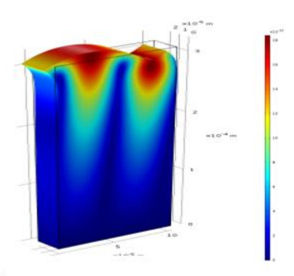
3. *The assumption of an inelastic and probably not isotropic scattering pattern on a separate nucleus is in contradiction with the basic principles underlying the existing theory of neutron wave dispersion*

Possible experimental approaches

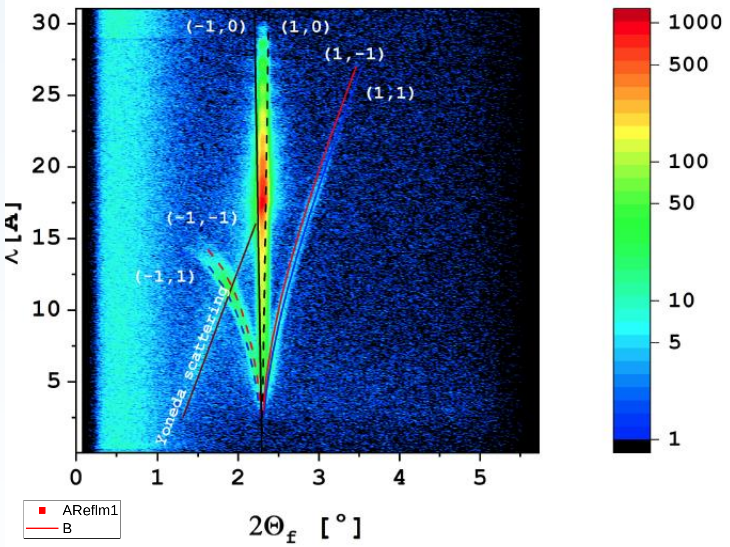
Using centripetal acceleration. Easily achievable accelerations $10^5 m/s^2$

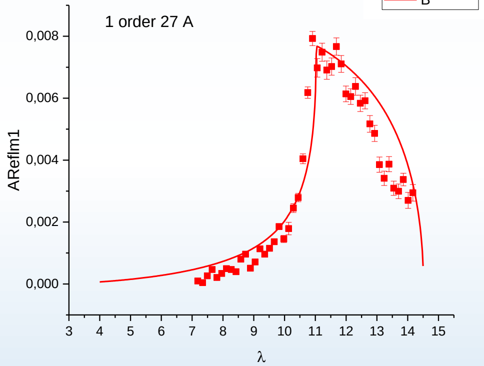


Neutron diffraction by SAW.
Acceleration of the surface and near-surface layer up to $10^9 m/s^2$



Calculated by S.V.Goryunov





Poster of G. Kulin

Conclusion

Any object that scatters a wave or receives and then emits a signal shifts its frequency 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

Thank you for your attention!