



Frequency shift at interaction of waves with accelerating object

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(New view at the concept of Accelerating Matter Effect)

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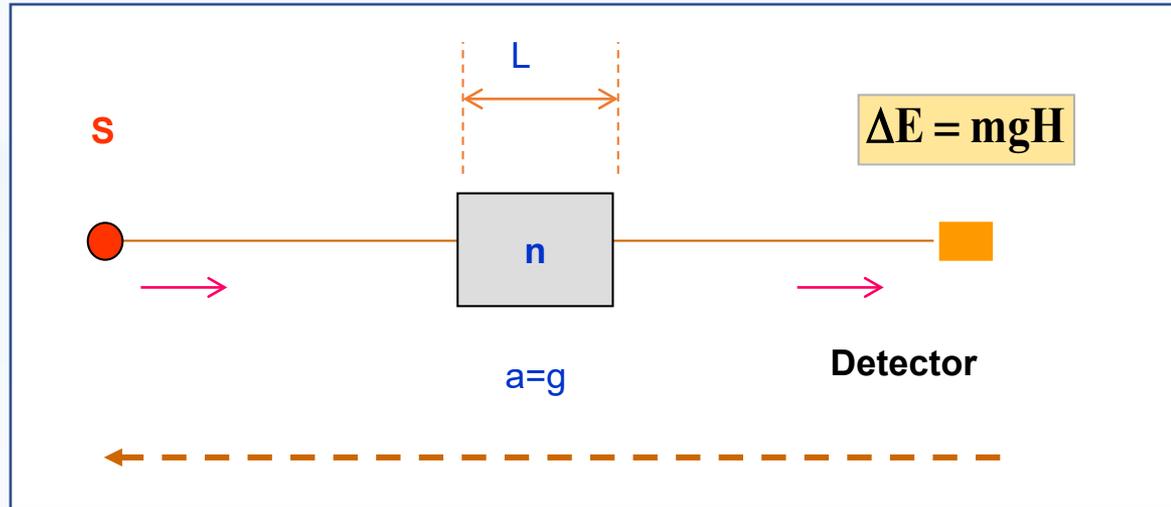
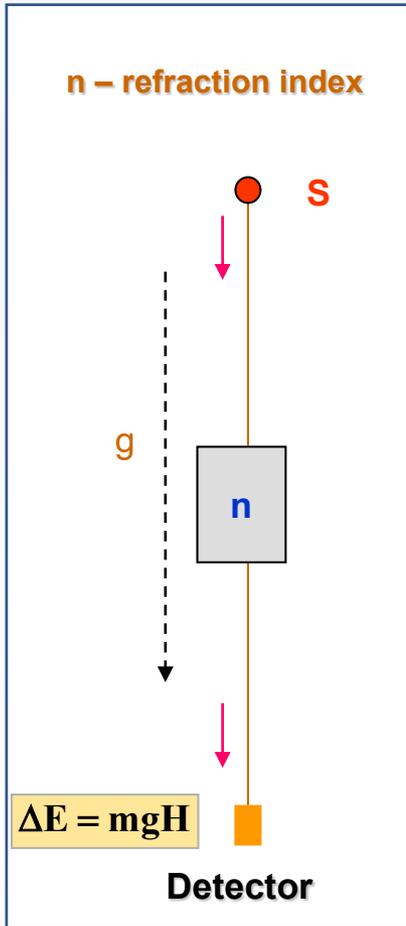
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*The equivalence principle
and
Accelerating Matter Effect*

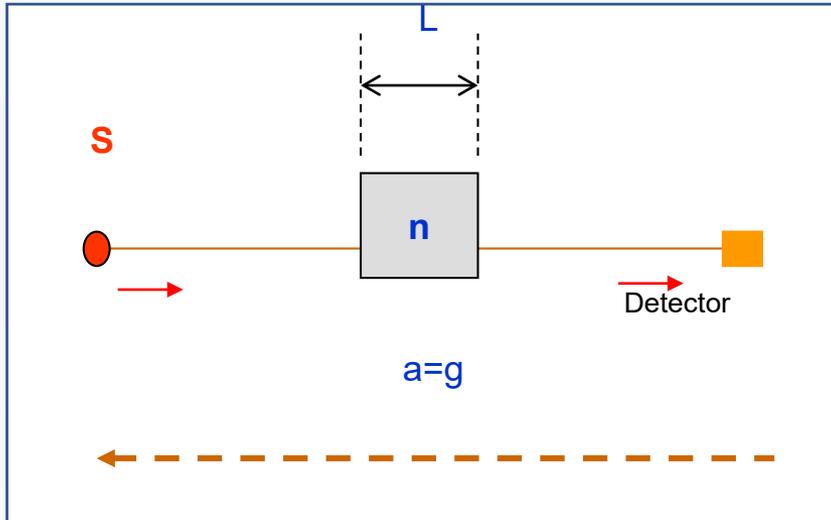
Accelerating sample and the equivalence principle



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 $\Delta\tau$ $\Delta v = a\Delta\tau$

During this delay time the detector will continue to accelerate

Accelerating sample and the equivalence principle



$$\Delta v = a\Delta\tau$$

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

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**

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

Light

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

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

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

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

Neutrons

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

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

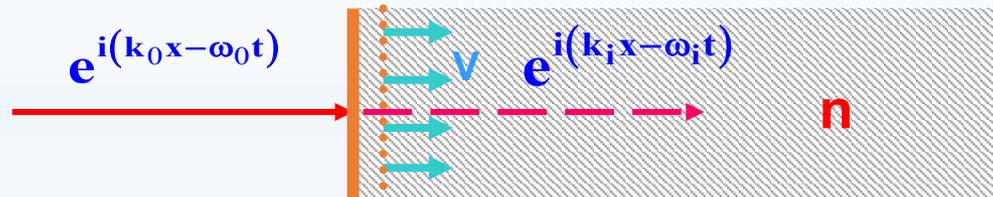
$$\Delta E \cong mad \left(\frac{1}{n} - 1 \right)$$

F. V. Kowalski. Phys. Lett. A., **182**, 335 (1993)

V.G. Nosov and A.I. Frank. Phys. of At. Nucl., **61**, 613 (1998)

*Physical explanation of the
AME as an optical
phenomenon –
differential Doppler effect at
refraction.*

Refraction of a wave at the border of the moving matter



$$\mathbf{k}_i = n\mathbf{k}_0 \left(1 + \frac{1-n}{n} \frac{\mathbf{V}}{v_0} \right)$$

$$\omega_i = \omega_0 + (n-1) \mathbf{k}_0 \mathbf{V}$$

Doppler shift

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

Massive particle (neutron)

$$\mathbf{k}_0 = \frac{m\mathbf{v}_0}{\hbar} \quad \left(\frac{V}{v_0} \ll 1 \right)$$

$$n \equiv n(k'_0) = n(k_0 - k_v)$$

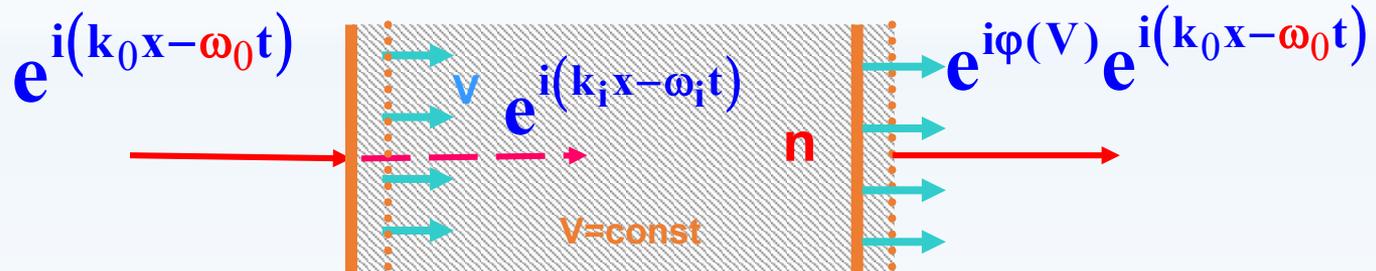
Light

$$\mathbf{k}_0 = \frac{\omega_0}{c} \quad \left(\frac{V}{c} \ll 1 \right)$$

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

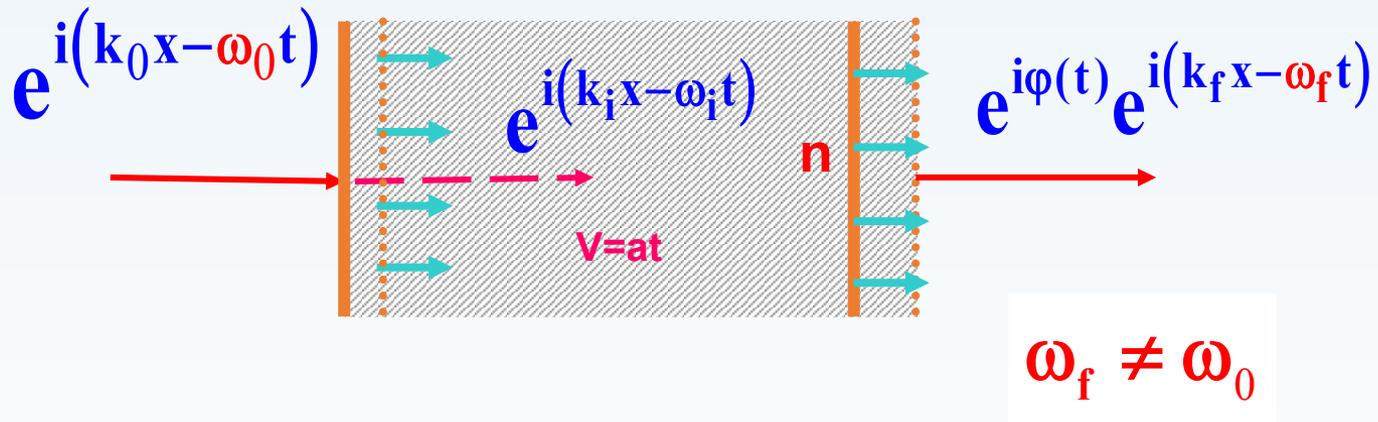
Fresnel drag

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



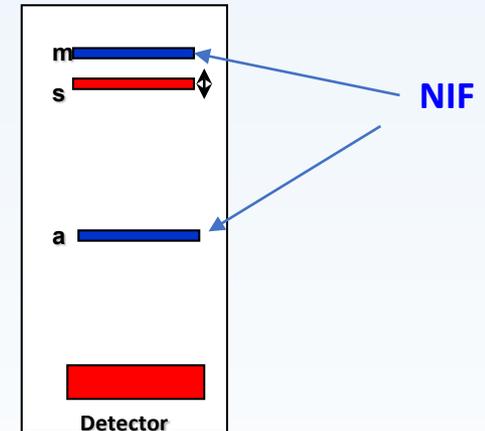
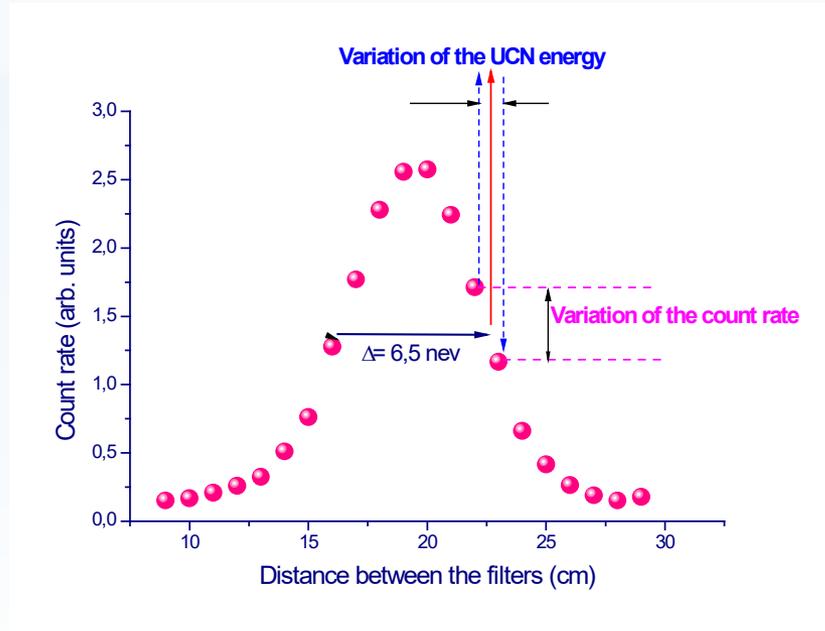
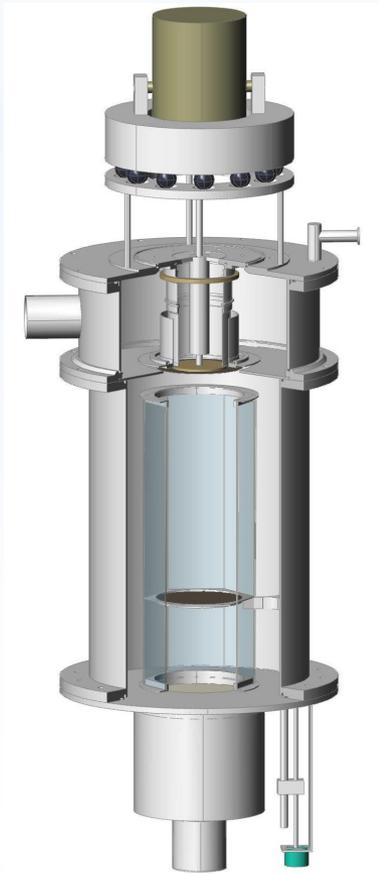
When the wave enters into the sample from free space, the frequency of the wave suffers frequency shift. When the wave comes out of the medium into free space, the frequency of the wave suffers an inverse frequency shift. For the constant-velocity motion, these two frequency shifts cancel each other.

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



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

*Observation of the AME in the
experiments with UCN
(2006-2008)
and thermal neutrons
(2014-2017)*

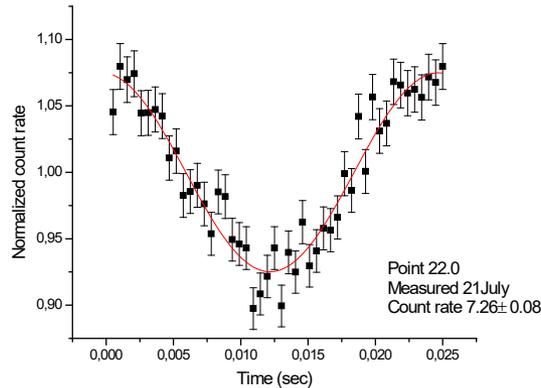


$$\Delta E \approx (2-5) \times 10^{-10} \text{ eV}$$

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

Experimental observation of AME with UCNs (1)

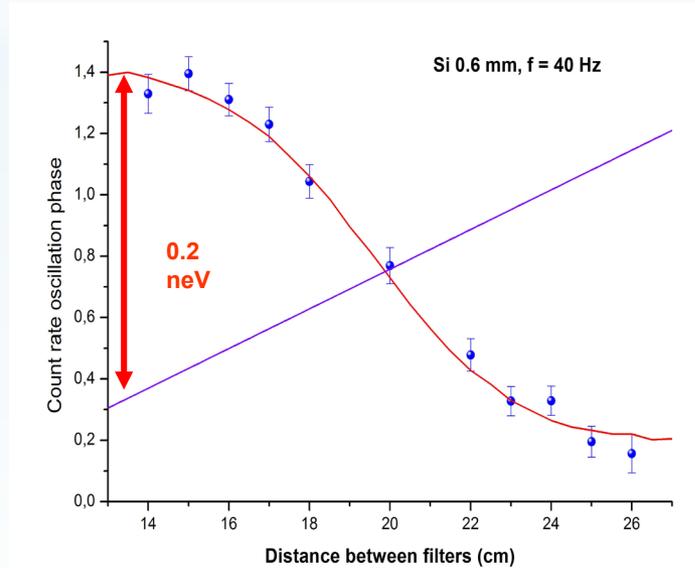
A.I. Frank, P.Geltenbort, G.V.Kulin, et al, Phys. At. Nuclei, 71 (2008) 1656.



$$a \cong -A\Omega \sin \Omega t \quad v \cong A\Omega \cos \Omega t$$

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

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

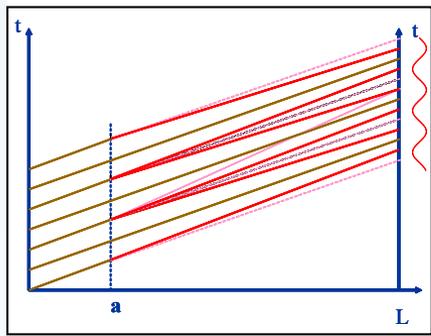


$$w_{\max} = A\Omega^2 \approx 60 \text{ m} / \text{s}^2$$

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

$$K = 0.94 \pm 0.06$$

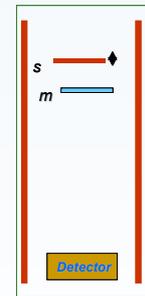
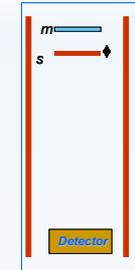
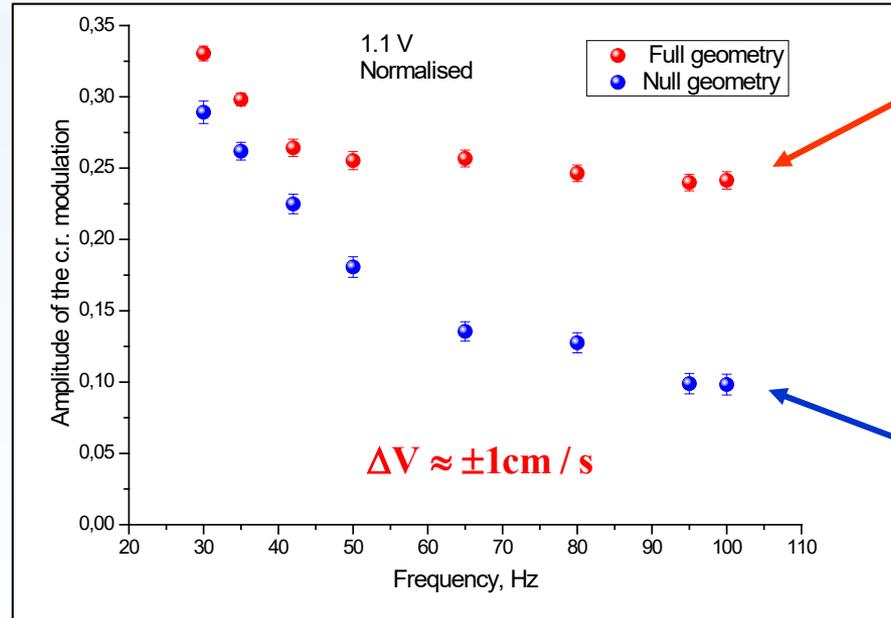
A. I. Frank, P. Geltenbort, M. Jentschel, et al. JETP Letters, **93** 361(2011)



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

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

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



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

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

$$\frac{\Delta V_{\text{exp}}}{\Delta V_{\text{th}}} = 0.95 \pm 0.10_{\text{stat}} \pm 0.05_{\text{syst}}$$

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

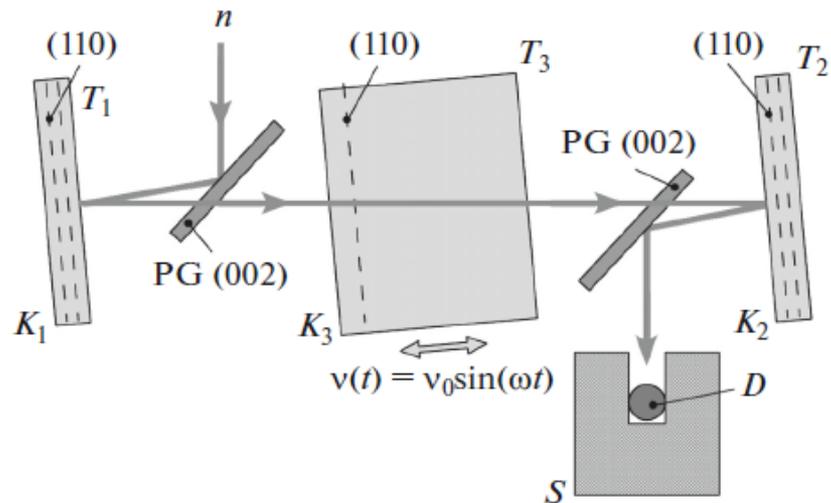


Fig. 1. Scheme of experimental setup: (n) collimated neutron beam, (K_{1-3}) quartz single crystals of temperature T_{1-3} , (PG) pyrolytic-graphite crystals, (D) neutron detector, and (S) detector shield.

Change of the energy was observed but interpretation of the effect is debatable

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

AME was predicted for light, neutrons, and neutrinos though was observed only for neutrons.

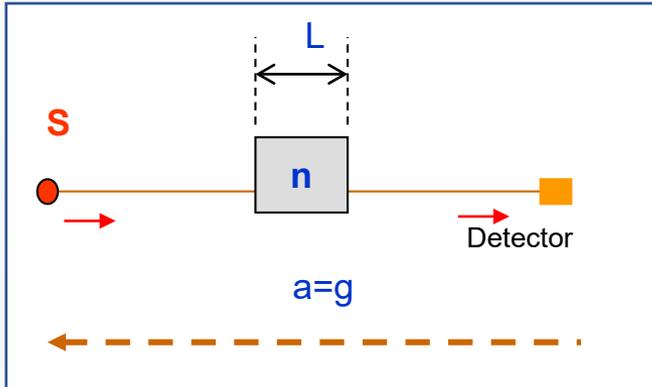
Soon after its observation we concluded that AME is very general optical effect because the concept of the refraction index must be introduced for any particles.

It is enough only that media contains any scattering center

$$\mathbf{n}^2 = 1 + \frac{4\pi}{\mathbf{k}_0^2} \mathbf{N} \mathbf{f}(0 \rightarrow 0)$$

But it is really only optical effect?

Accelerating sample and the equivalence principle again



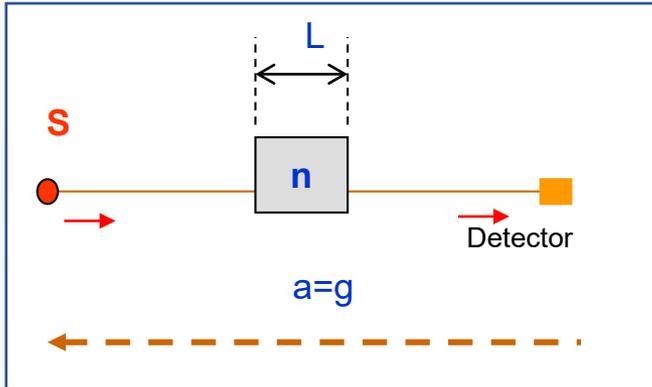
$$\Delta v = a \Delta \tau$$

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

We concluded that 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

It is not correctly to associate the delay time $\Delta \tau$ only with refraction

Accelerating sample and the equivalence principle again



$$\Delta v = a \Delta \tau$$

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We concluded that 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

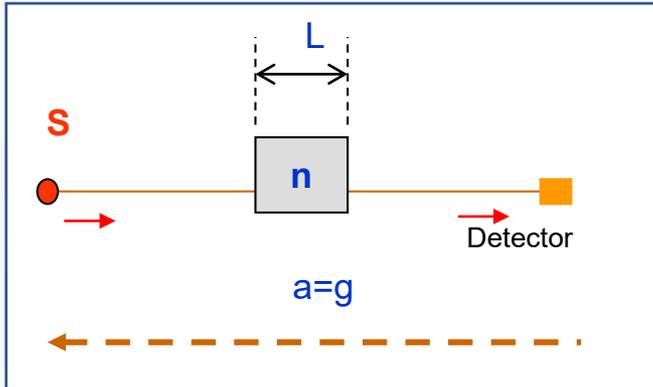
It is not correctly to associate the delay time $\Delta \tau$ only with refraction.

All interactions necessary related with time delay.

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

Group delay time
(Bohm, Wigner, 1952-55)

Accelerating sample and the equivalence principle again



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Group delay time (Bohm, Wigner, 1952-55)

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

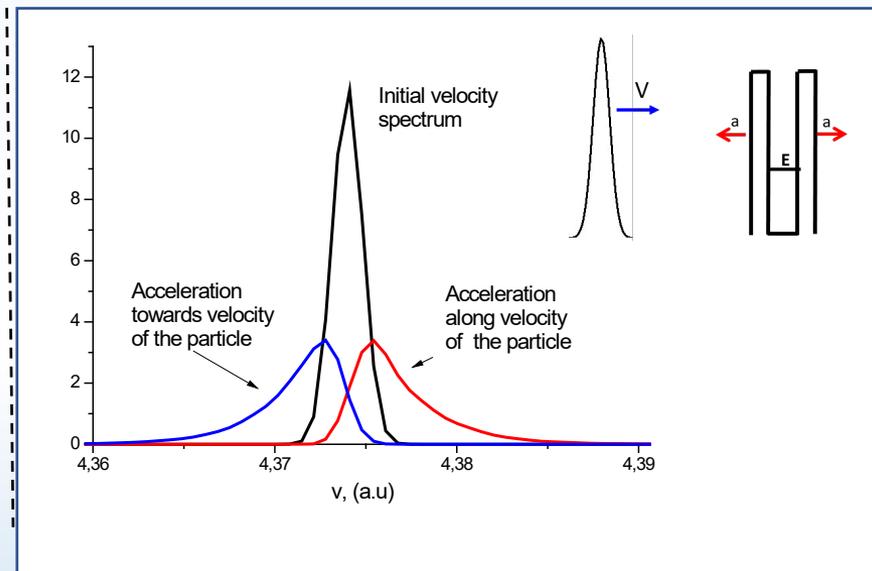
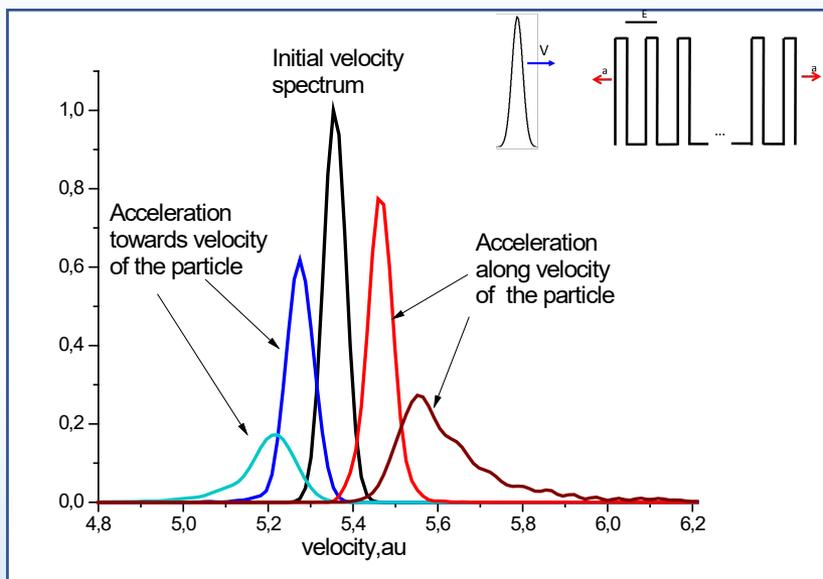
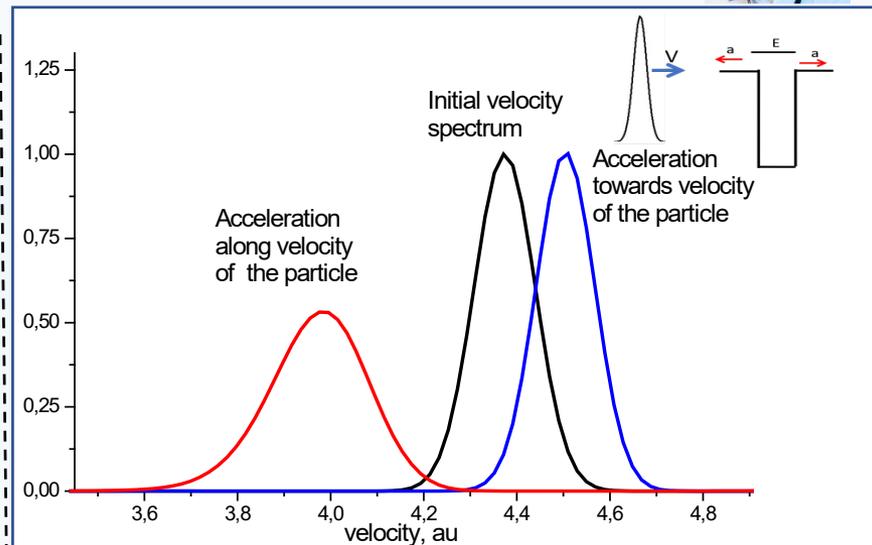
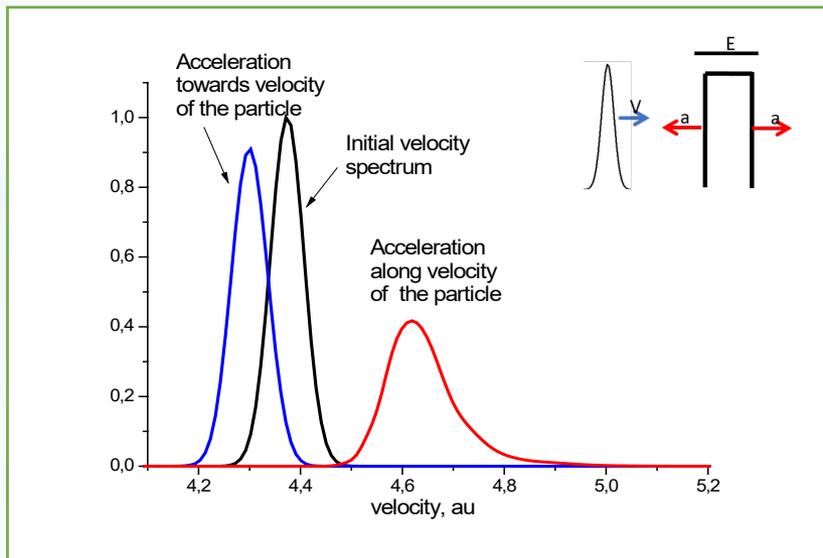
Any device which is transmitting signals always doing that with a delay

General equation

$$\Delta\omega = ka\Delta\tau$$

*Microscopic accelerating
objects*

Quantum calculations of the wave packet interaction with an object (M. Zakharov)



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

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

Scattering amplitude

GDT $\tau = \hbar \frac{d\varphi}{dE}$ $\varphi = \text{arctg} \left(\frac{f''}{f'} \right) \approx \frac{f''}{f'} \quad (f'' \ll f')$

Optical theorem $\sigma_t = \sigma_s + \sigma_a = \frac{4\pi}{k} f''$ σ_t - total cross-section
 σ_s - scattering cross-section
 σ_a - capture cross-section
 $\sigma_s = 4\pi (f')^2$

$$\varphi = \frac{f''}{f'} = \frac{k\sigma_t \sqrt{4\pi}}{4\pi \sqrt{\sigma_s}} = \frac{k(\sigma_s + \sigma_a)}{\sqrt{4\pi\sigma_s}} \quad k\sigma_a = \text{const} \quad \tau = \hbar \frac{d\varphi}{dE} = \frac{1}{v} \sqrt{\frac{\sigma_s}{4\pi}}$$

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

For thermal neutrons $\tau \approx 10^{-17} \text{ s}$

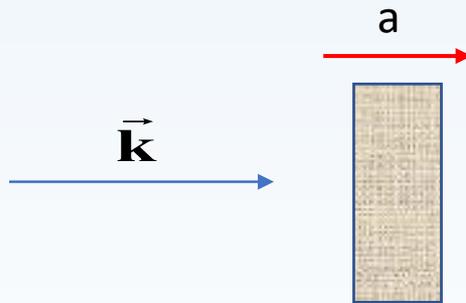
For UCN $\tau \approx 10^{-14} \text{ s}$

$$\Delta v = a \Delta \tau$$

The energy transform at the neutron scattering at the nucleus moving with acceleration

$$\Delta v = a \Delta \tau$$

$$\Delta E = mv \cdot \Delta v = 2E \frac{\Delta v}{v}$$



$$U = (\neq ?) \frac{2\pi\hbar^2}{m} \rho b$$

Since the neutron energy changes during scattering by accelerating nuclei, the concept of a constant effective potential is not entirely true for the case of neutron interaction with accelerating matter.

In the case of surface acoustic waves the acceleration of the near-surface region of matter is of the order

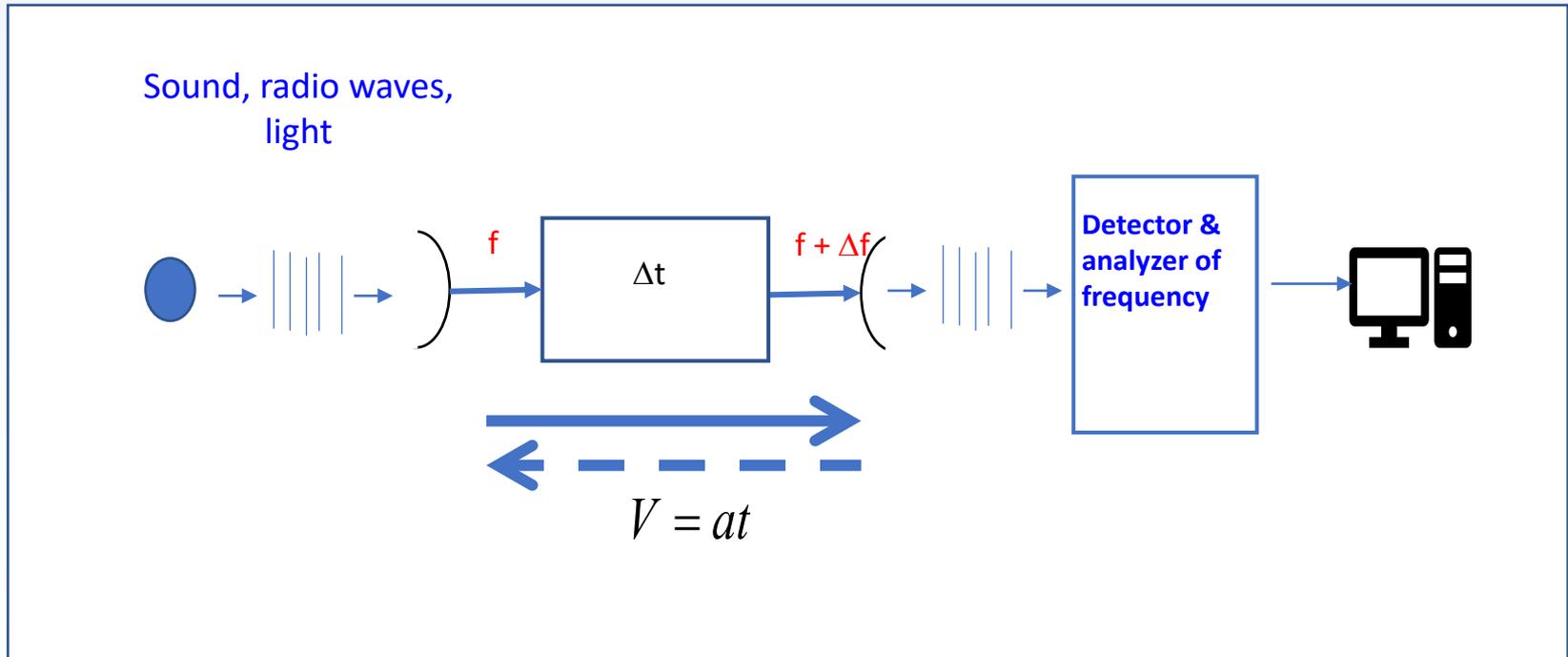
$$10^{10} \div 10^{11} \text{ cm} / \text{s}^2$$

For UCN

$$\Delta E \approx 5 \cdot 10^{-13} \text{ eV}$$

*Macroscopic accelerating
object*

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



Conclusion

Interaction of particle with an accelerating object results in the change in its energy

Any devices that receive and then emit a wave shift its frequency if they move with acceleration

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Acknowledgments

Many thanks to G. Arzumanyan, V. Bushuev, S. Goryunov, G.Kulin and M. Zakharov for very fruitful discussions

Conclusion

Interaction of particle with an accelerating object results in the change in its energy

Any devices that receive and then emit a wave shift its frequency if they move with acceleration

Acknowledgments

Many thanks to G. Arzumanyan, V. Bushuev, S. Goryunov, G.Kulin and M. Zakharov for very fruitful discussions

Thank you for your attention!