The equivalence principle and interaction of waves with an accelerating object

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ISINN 27, 10-14 June, Dubna

Accelerating Matter Effect (chronology)

- **1977. V. Mikerov numerically investigated the problem of UCN transmission through the oscillating foil and found that the neutron energy do not conserved at the passing through it.** *V.I. Mikerov. PHD thesis, Lebedev Physical Institute, 1977 (was not published)*

- **1982. Kazuo Tanaka solved the problem of transmission of electromagnetic waves through the linearly accelerating dielectric slab and found that there exists shift in frequency. This shift depends on the acceleration but not on the velocity** *K. Tanaka. Phys. Rev. A., **25**, 385 (1982)*

- **1993. F.W. Kowalski looking for the new approach to the test of the equivalence principle (EP) in neutron optics. Solving the problem of neutron transmission through the accelerating sample came to the contradiction with EP but found that neutron frequency (and energy) change when neutron passes through an accelerating sample.** *F. V. Kowalski.Phys. Lett. A.,**182,** 335 (1993)*

- **1998. V.G. Nosov and A.I. Frank considered the problem of transmission of neutron wave through the refracting sample moving with acceleration and confirmed the Kovalski formula for the energy change.** *V.G. Nosov and A.I.Frank. Phys. of Atomic Nuclei, 61, 613 (1998)*

- **2006. FLNP-ILL group firstly detected the change of the UCN energy at transmission through the oscillating silicon slab with quality agreement with Kowalski-Nosov-Frank (KNF) formula.** *A.I.Frank et al. JETP letters, **84,** 363 (2006)*

- **2008. KNF formula and Tanaka formula were derived in a uniform way from the equivalence principle. The term "Accelerating matter effect" (AME) was introduced.** *A.I.Frank et al. Phys. of Atomic Nuclei, 71, 1656 (2008)*

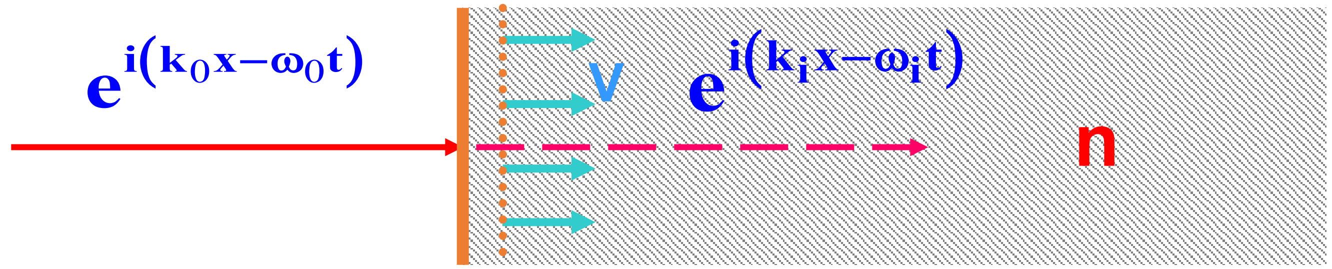
- **2008, 2011. New observation of AME in the agreement with theory at the level 5-7%.** *A.I.Frank et al. Phys. of Atomic Nuclei, 71, 1656 (2008), JETP letters, **93,** 361 (2011)*

- **2013г. KNF formula for the neutron wave was derived from the Doppler effect at refraction. The problem of AME for the birefringent medium was analyzed. AME for neutrino was predicted.** *A.I.Frank and V.A.Naumov. Phys. of Atomic Nuclei, **76**,1423 (2013)*

- **2014г. Observation of the neutron acceleration at diffraction by a oscillating crystal.** *V.V. Voronin et al., JETP letters, 100, 497 (2014)*

Doppler effect at refraction

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

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

Massive particle (neutron)

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

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

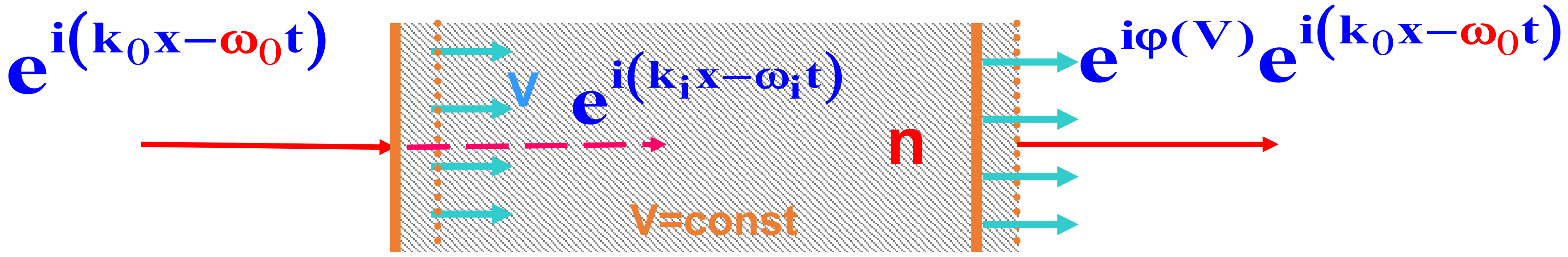
Light

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

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

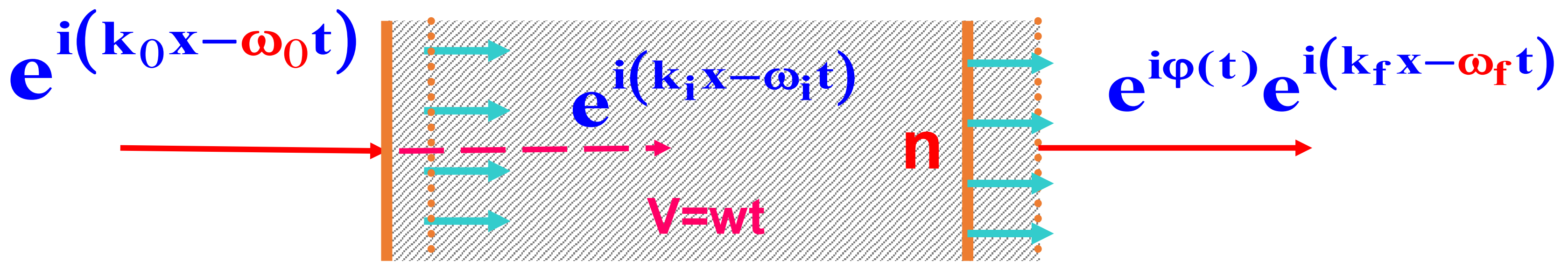
Fresnel drag

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



When the wave enters 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)



$\omega_f \neq \omega_0$

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

Differential Doppler effect and Accelerating Matter Effect

$$\omega_i = \omega_0 + (n'-1)k_0 V \qquad (V << v_0)$$

$$\Delta\omega = (n'-1)k_0 V - (n'-1)k_0(V + w\Delta t) = k_0 w(1-n')\Delta t \qquad \Delta t = \frac{d}{n' v_0}$$

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

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

Kowalski-Nosov-Frank

Assumptions:

1) Model of effective optical is also valid in the case of accelerating matter
2) Quasi – classical approach is correct

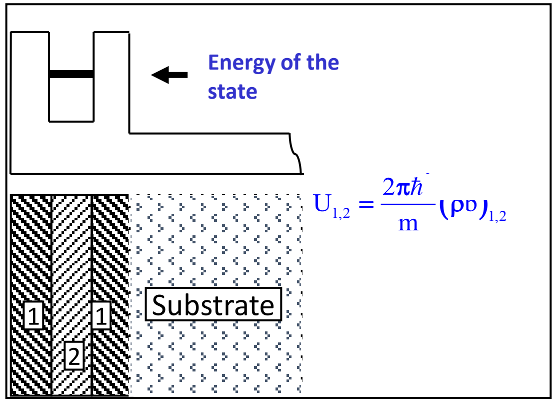
FLNP

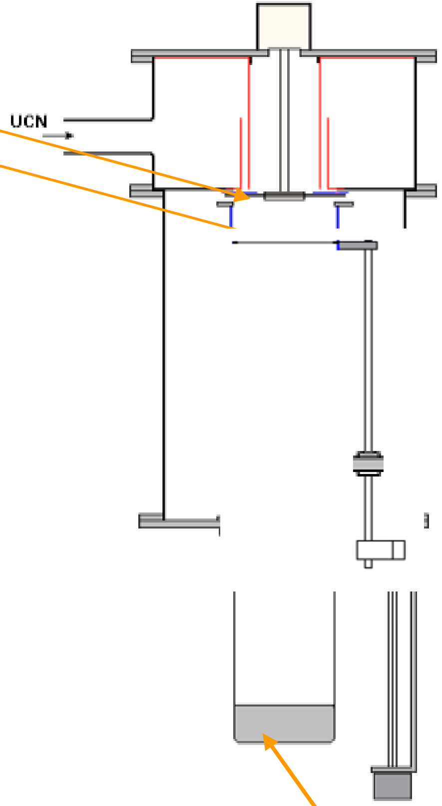
Observation of the AME in the experiments with UCN (2006-2008) and thermal neutrons (2014-2017)

UCN spectrometry with Fabry-Perot interferometers

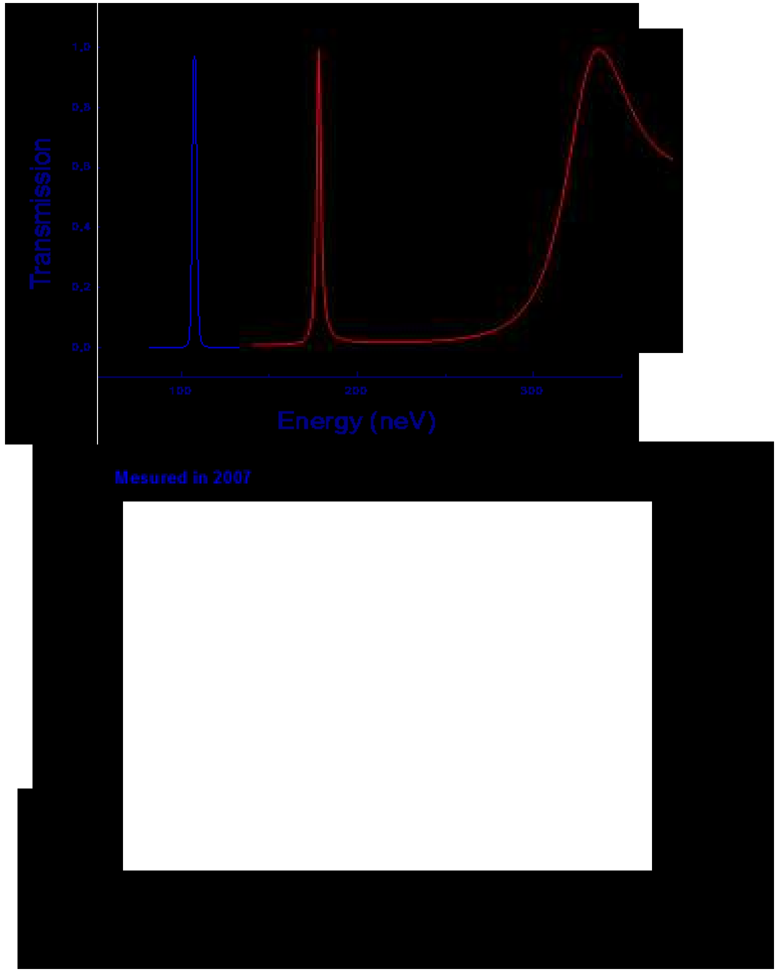
Two IFP with variable space between them

mg=1.02 neV/cm

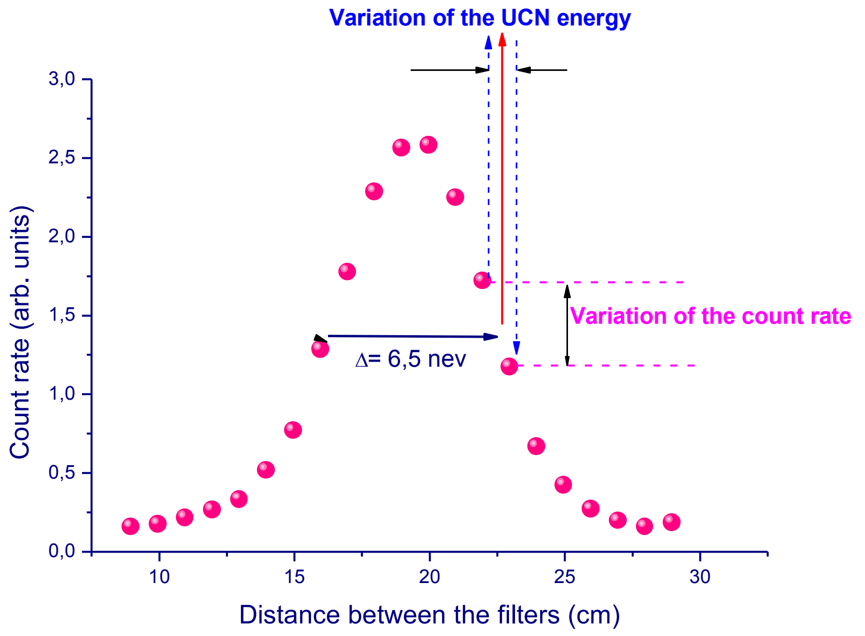


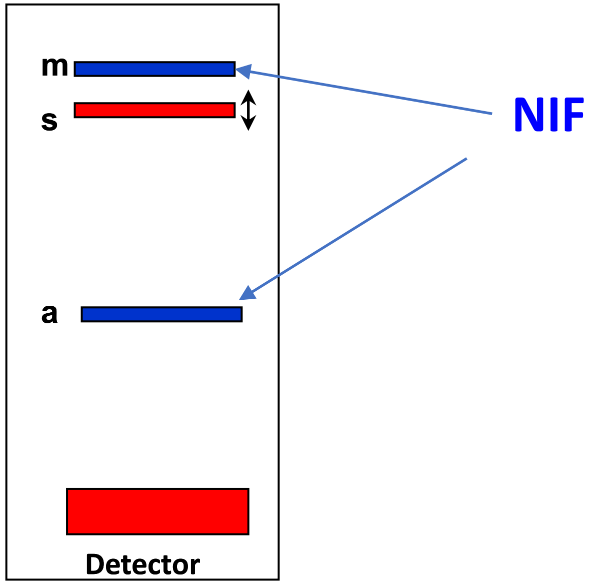


Detector



Principle of the AME experimental observation

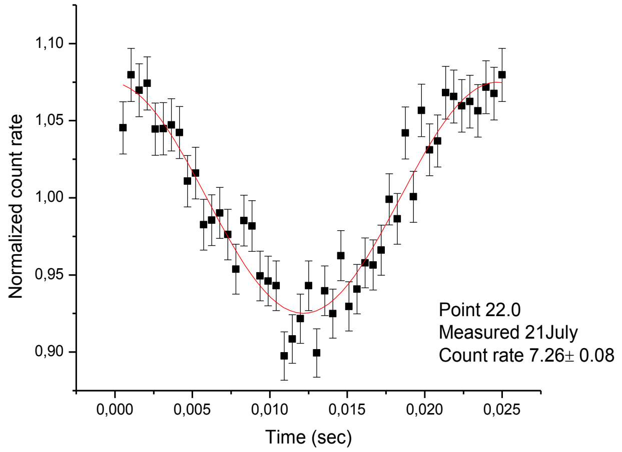


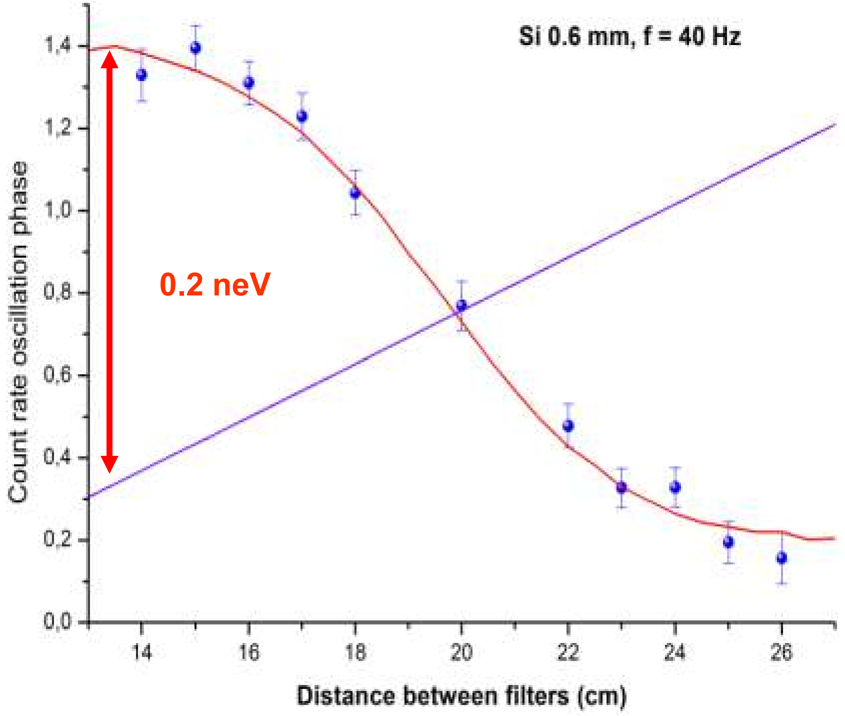


$\Delta E \approx (2\text{-}5)\times 10^{-10}$ eV

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

Oscillation of the count rate and experimental result





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

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

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

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

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

$$K = 0.94 \pm 0.06$$

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

Diffraction experiment of the PNPI group

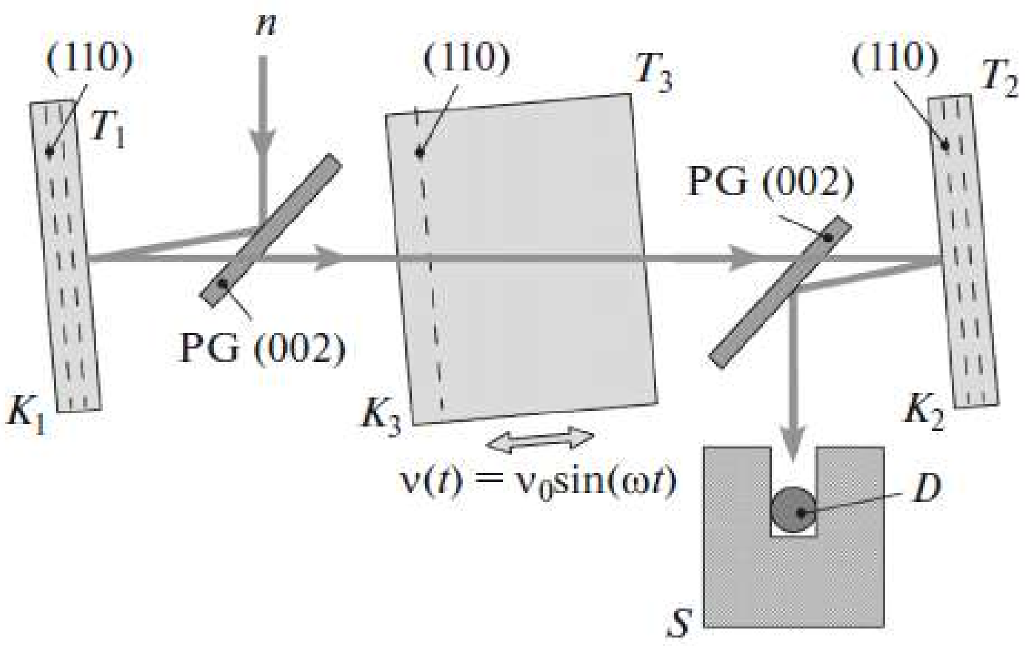


Fig. 1. Scheme of experimental setup: (n) collimated neutron beam, (K_{1-3}) quartz single crystals of temperature T_{1-3}, (PG) pyrolytic-graphite crystals, (D) neutron detector, and (S) detector shield.

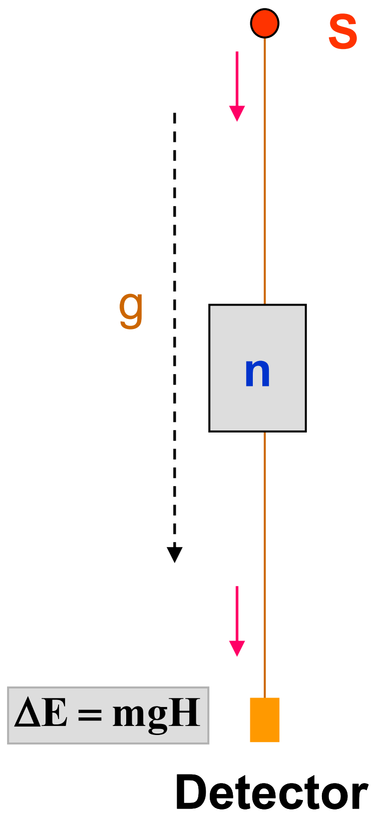
Change of the energy was observed but interpretation of the effect is debatable

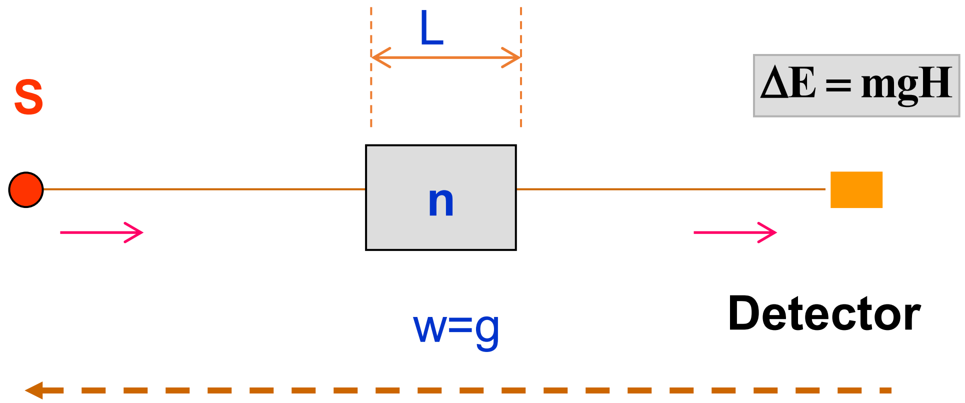
V.V. Voronin et al., JETP letters, 100, 497 (2014)
Yu. P. Braginetz et al.,Phys.At. Nucl. 80, 32 (2017)

The equivalence principle and Accelerating Matter Effect

Accelerating sample and the equivalence principle

n – refraction index



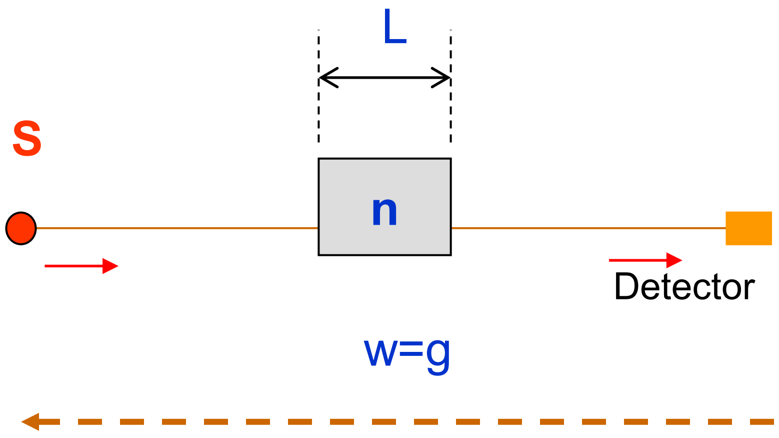


1. In both cases the energy, measured by the detector, must be the same due to the equivalence principle
2. Introduction of the refracting slab does not change the energy due to the energy conservation law (see left fig.)
3. Delay time due to refraction is $\Delta\tau$

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

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

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

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

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

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

KNF formula

UCNs

Si $d \approx 0.6$ mm, $w \approx 10$ g

$$\frac{\Delta E}{E} \approx 3\times10^{-3}$$

Light

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

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

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

Tanaka formula

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

$$\frac{\Delta\omega}{\omega} = 5\times10^{-15}$$

Change of the frequency appears due to delay of the wave in a sample, which are moving with acceleration

Neutrons

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

$$\Delta E = mv \cdot \mathrm{w}\Delta\tau$$

Light and relativistic parrticle

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

$$\Delta\omega = \omega \frac{\mathrm{w}\Delta\tau}{c}$$

General equation

$$\Delta\omega = k\mathrm{w}\Delta\tau$$

But why the time delay related only with refraction?

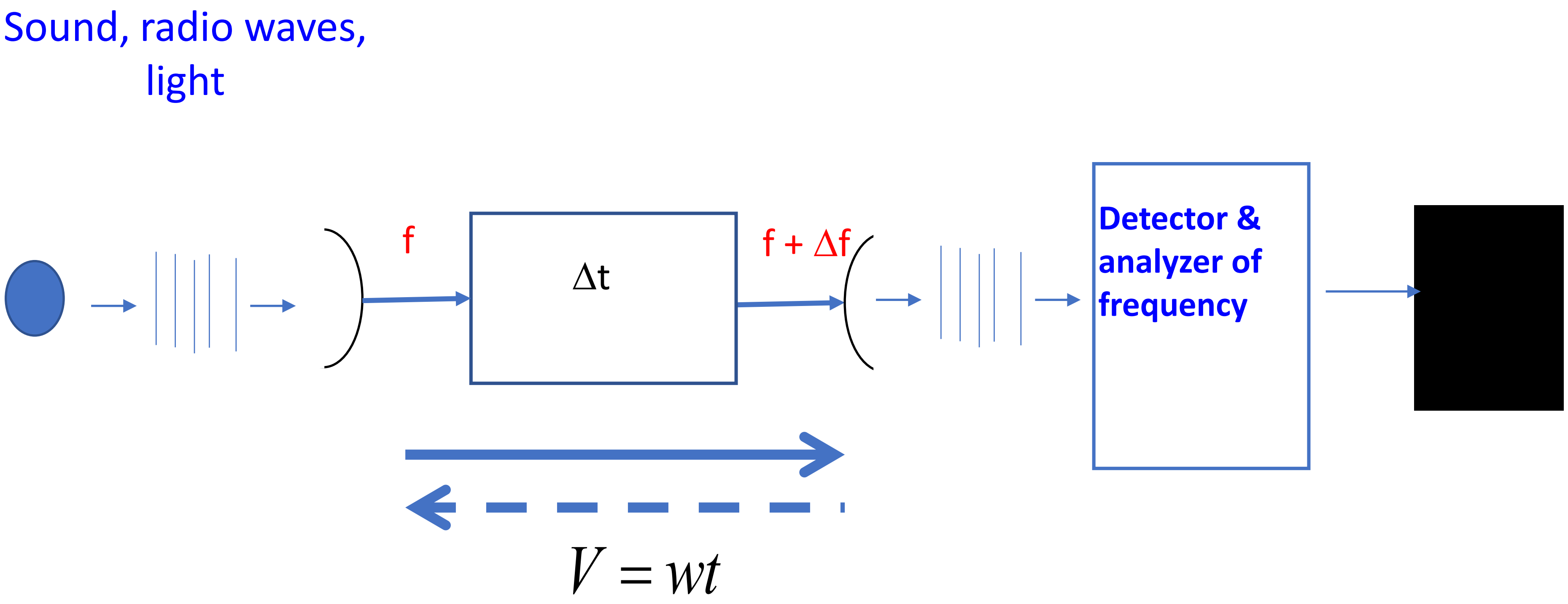
Any object which transmitting narrow-band signal with delay shifts frequency if it is moving with acceleration.

1. *Any interaction necessary related with time delay*
2. *Any device which is transmitting signals always doing that with delay*

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

Two examples of accelerating object

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



FLNP

Group delay time at neutrons scattering at atomic nucleus

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

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

Scattering amplitude

GDT $\quad \tau = \hbar \dfrac{d\varphi}{dE} \qquad \varphi = \mathrm{arctg}\left(\dfrac{f''}{f'}\right) \approx \dfrac{f''}{f'}$

Optical theorem $\quad \sigma_t = \sigma_s + \sigma_a = \dfrac{4\pi}{k} f''$

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

σ_t - total cross-section

σ_s - scattering cross-section

σ_a - capture cross-section

Group delay time at neutrons scattering at atomic nucleus

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

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

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

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

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

time of flight of nucleus

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

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

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

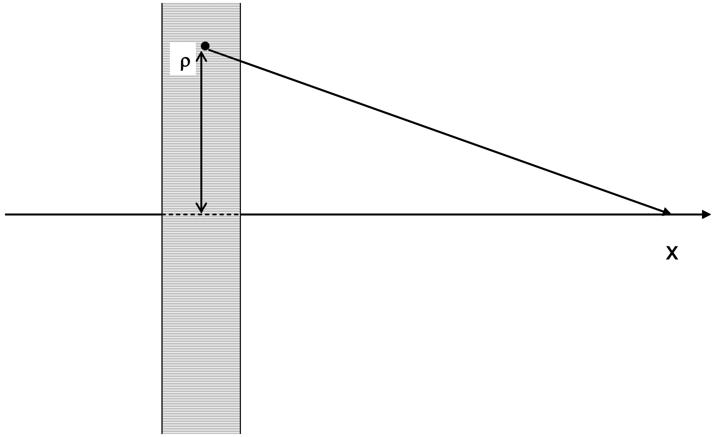
$$\Delta v = w\Delta\tau \qquad \Delta E = mv \cdot \Delta v = 2E\frac{\Delta v}{v} \qquad \Delta v = w\tau$$

At SAW propagation the acceleration of the near-surface region is of the order

$$w \approx 10^{10} \div 10^{11}\, cm/s^2$$

For UCN $\Delta E \approx 5 \cdot 10^{-13}\, eV$

Solving the problem of neutron scattering by a sole accelerating nucleus it is possible to formulate the dispersion theory of neutron in the accelerating matter in analogy with Fermi's theory for refraction index.



Conclusion

Any object receiving and then radiating a wave shifts its frequency if it is moving with acceleration

Acknowledgments

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

Thank you for your attention!