Investigation of a neutron diffraction at surface acoustic waves

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V.A. Bushuev Yu.N. Khaydukov D.V. Roschupkin

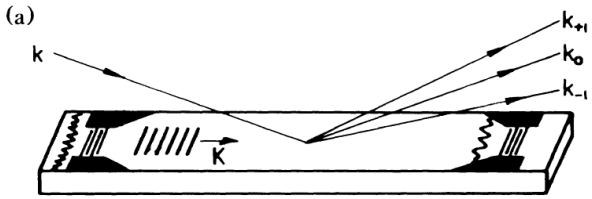
I.M. Frank JINR Comm. R4-8851 (1975) - possibility of inelastic process of neutron diffraction on surface (Rayleigh) waves in connection with the so-called UCN storage anomaly.

UCN scattering for the case of waves at the surface of a fluid:

Yu. N. Pokotilovski. Phys. Lett A, 255, (1999) 173

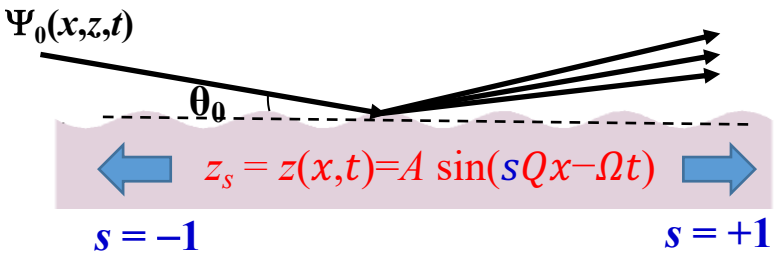
S. K. Lamoreaux and R. Golub, Phys. Rev. C 66, 044309 (2002)

W.A. Hamilton, A.G.Klein, G.I.Opat and P.A.Timmins. Phys. Rev. Lett. 58 (1987) 2770



First direct experiment aimed at observing neutron diffraction on travelling surface acoustic wave (SAW) excited on the surface (quartz plate)

Diffraction of neutrons on travelling SAW



$$\Omega = 2\pi V/\Lambda \qquad Q = 2\pi/\Lambda = \Omega/V$$

$$\Psi_0(x,z,t) = \exp\left(ik_{0x}x + ik_{0z}z - i\omega_0 t\right)$$

Due to diffraction on SAW:

$$\Psi_R(x,z,t) = \sum_{n=-\infty}^{\infty} r_n \exp(ik_{nx}x - ik_{nz}z - i\omega_n t)$$

$$\Psi_T(x,z,t) = \sum_{n=-\infty}^{\infty} t_n \exp(ik_{nx}x + iq_{nz}z - i\omega_n t)$$

At the interface z_s (boundary conditions):

$$\Psi_0\left(x,z_s,t\right) = \sum_{m=-\infty}^{\infty} J_m(k_{0z}A)\exp(ik_{mx}x - i\omega_m t) \qquad k_{mx} = k_{0x} + smQ \qquad \omega_m = \omega_0 + m\Omega$$

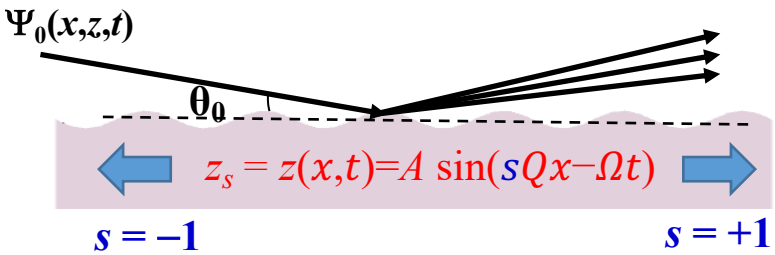
$$\Psi_T(x,z_s,t) = \sum_n \sum_{m'} t_n J_{m'}(q_{nz}A)\exp[i(q_{nx} + m'Q)x - i\left(\omega_n + m'\Omega\right)t].$$

$$\Psi_R(x,z_s,t) = \sum_n \sum_{m'} r_n J_{m'}(-k_{nz}A)\exp[i(k_{nx} + sm'Q)x - i\left(\omega_n + m'\Omega\right)t]$$

$$q_{nx} = k_{nx} \qquad q_{nz} = \sqrt{k_{nz}^2 - k_b^2}$$ **Neutron wave number in a matter**

$$k_b = \sqrt{2MU_0}/\hbar$$ **critical wave number**

Diffraction of neutrons on travelling SAW



$$\Omega = 2\pi V/\Lambda \qquad Q = 2\pi/\Lambda = \Omega/V$$

$$\Psi_0(x,z,t) = \exp\left(ik_{0x}x + ik_{0z}z - i\omega_0 t\right)$$

Due to diffraction on SAW:

$$\Psi_R(x,z,t) = \sum_{n=-\infty}^{\infty} r_n \exp(ik_{nx}x - ik_{nz}z - i\omega_n t)$$

$$\Psi_T(x,z,t) = \sum_{n=-\infty}^{\infty} t_n \exp(ik_{nx}x + iq_{nz}z - i\omega_n t)$$

Continuity equations at the interface z_s (boundary conditions):

$$J_m\left(k_{0z}A\right) + \sum_n r_n J_{m-n}\left(-k_{nz}A\right) = \sum_n t_n J_{m-n}\left(q_{nz}A\right)$$

$$k_{0z}J_m\left(k_{0z}A\right) - \sum_n r_n k_{nz} J_{m-n}\left(-k_{nz}A\right) = \sum_n t_n q_{nz} J_{m-n}\left(q_{nz}A\right)$$

At experimental conditions arguments of Bessel functions J_m are small ($n, m = 0, \pm 1$)

$$R_m = \left(k_{mz}/k_{0z}\right)\left|r_m\right|^2 \quad \Longrightarrow \quad R_0 = \left|\frac{k_{0z} - q_{0z}}{k_{0z} + q_{0z}}\right|^2, \quad R_{\pm 1} = k_{0z}k_{\pm 1z}A^2\left|\frac{k_{0z} - q_{0z}}{k_{\pm 1z} + q_{\pm 1z}}\right|^2$$

$$k_{\pm 1z} = \sqrt{k_{0z}^2 \pm 2Q(k_V - sk_{0x})} \qquad q_{\pm 1z} = \sqrt{k_{\pm 1z}^2 - k_b^2} \qquad k_V = MV/\hbar$$

Intensities of diffraction orders:

$$R_m = (k_{mz} / k_{0z}) |r_m|^2 \longrightarrow R_0 = \left| \frac{k_{0z} - q_{0z}}{k_{0z} + q_{0z}} \right|^2, \quad R_{\pm 1} = k_{0z} k_{\pm 1z} A^2 \left| \frac{k_{0z} - q_{0z}}{k_{\pm 1z} + q_{\pm 1z}} \right|^2$$

$q_{nz} = \sqrt{k_{nz}^2 - k_b^2}$ **neutron wave number in a matter**

$k_b = \sqrt{2MU_0} / \hbar$ **critical wave number**

Validity of the potential dispersion law is supposed

Diffraction angles:

$$k_{mx} = k_{0x} + smQ \qquad \omega_m = \omega_0 + m\Omega$$

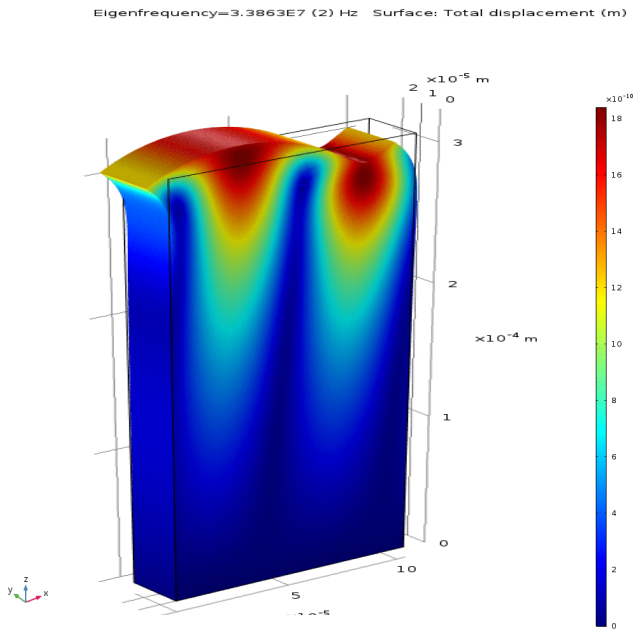
$$\Omega = 2\pi V / \Lambda \qquad Q = 2\pi / \Lambda = \Omega / V$$

$$\hbar\omega_m = \hbar^2 k_m^2 / 2M$$

$$k_V = MV / \hbar$$

$$\sin^2\theta_m = \sin^2\theta_0 + \frac{2mQ}{k_0}\left(\frac{k_V - sk_{0x}}{k_0}\right) - \frac{m^2 Q^2}{k_0^2}$$

Surface Acoustic Waves



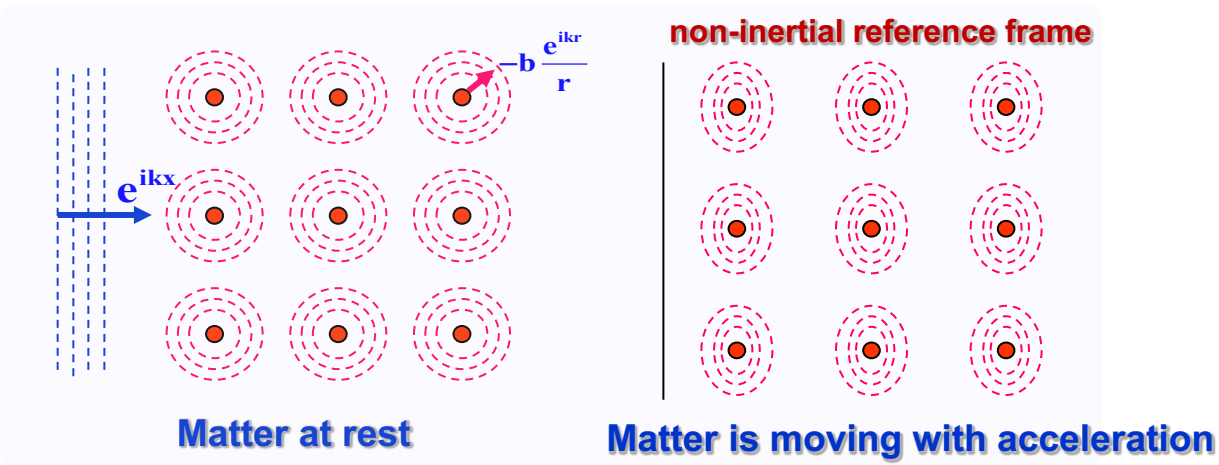
Calculated in COMSOL by S.V. Goryunov

- **SAW arise due to periodical oscillation of the near-surface layer of a matter that moves with alternative velocity and acceleration**
- **The depth of penetration of the Rayleigh wave into the matter is of the order of the SAW wavelength**

For a typical SAW with a frequency of tens MHz this acceleration reaches a value of 10^7g!!!

Is the commonly accepted theory of UCN interaction with matter is valid in this case ?

The theory of dispersion - the theory of multiple scattering of waves



Dispersion law of the neutron wave in accelerating matter — no any theoretical predictions at this moment

What is the region of validity of the potential dispersion law ?

The hypothesis: Potential dispersion law is valid if phase distortion due to accelerating appeared at the interatomic distance is much less than the phase shift *kb* due to scattering at the nuclei (A. I. Frank, *JETP Lett.*, 100, p. 613, 2014).

$$\Delta\phi_w = \frac{mwx^2}{2E} \ll \delta \cong kb$$

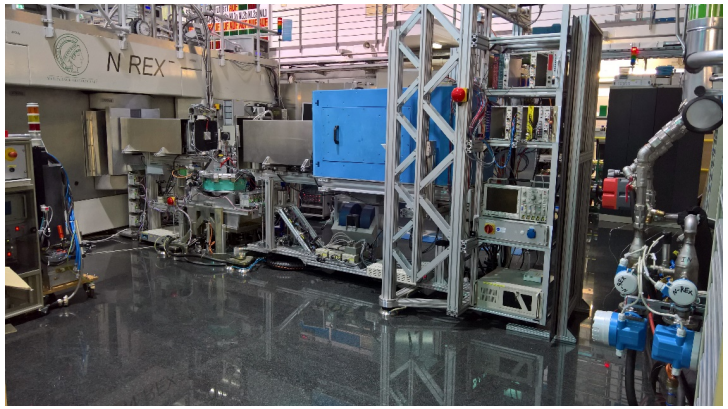
for $x \approx$ interatomic distance d

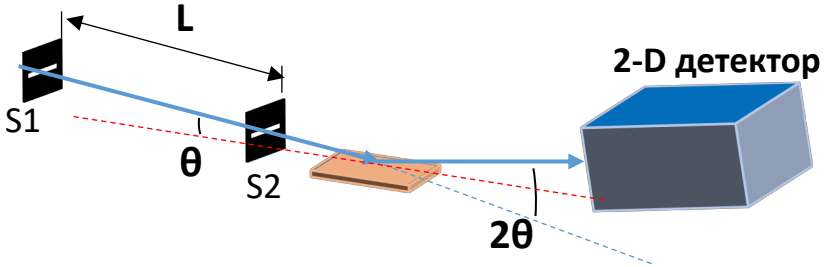
$$w \ll \frac{4Eb}{md^2} = w_{crit}$$

Are there any experimental results?

	Type of experiment	E, eV	Acceleration, m/sec^2	Critical accel., m/sec^2	Reference
1.	Reflection from surface acoustic waves	2.8×10^{-4} 6.7×10^{-4}	**6.3×10^{7}**	**2×10^{9}** **4.8×10^{9}**	W.A.Hamilton, A.G. Klein, G.I. Opat, P.A. Timmins, 1987
2.	Reflection from vibrating mirror	1.4×10^{-4}	**10^{6}**	**1.1×10^{9}**	J. Felber, R. Gahler, C. Rauch and R. Golub, 1996

There are no contradictions with hypothesis of critical acceleration

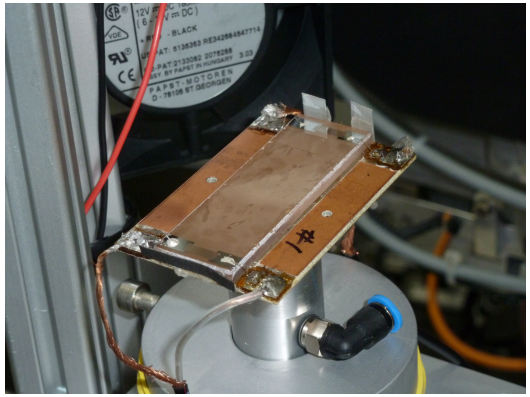




NREX+ Reflectometer (FRM II, Garching, Germany)

Neutron wave length: 4.3 Å
Wavelength resolution: 1-2%
Angular divergence: 0.7 mrad

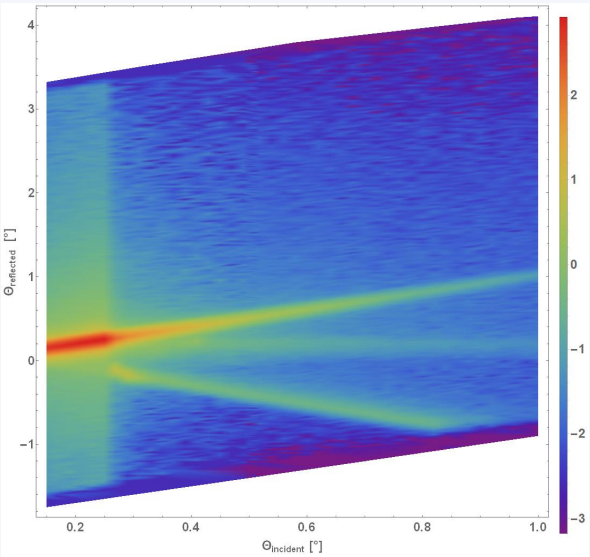
Sample: Single crystal Lithium Niobate ($LiNbO_3$)



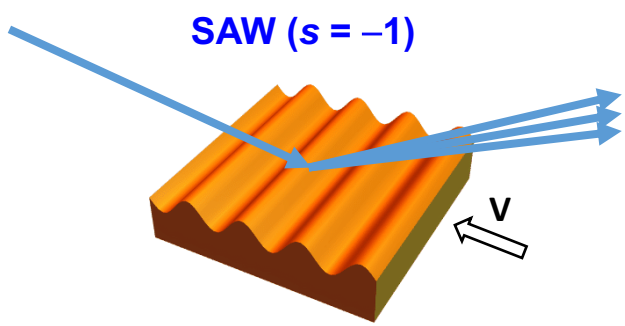
Size of Surface Wave Region: 0.5×6 cm^2
SAW velocity: 3490 m/sec > V_n = 920 m/sec (4.3 Å)
SAW frequency: 69 MHz
SAW amplitude: ~ 2 nm
SAW wavelength: ~ 50 mkm

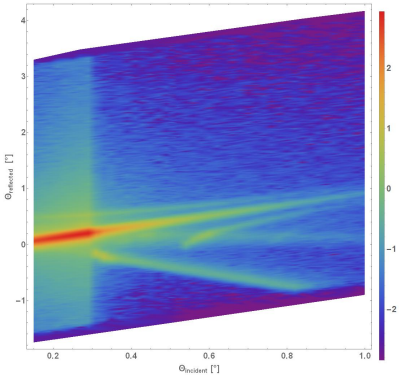
$\Delta E \approx 290$ neV (!)

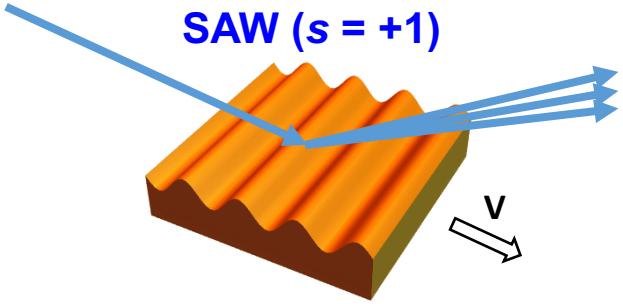
SAW travelling direction

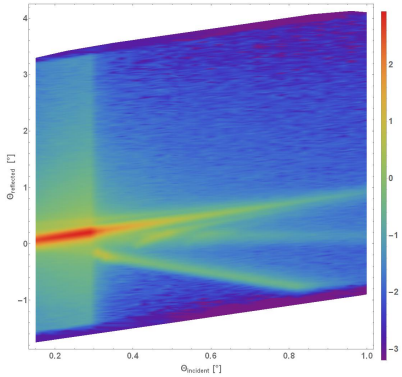


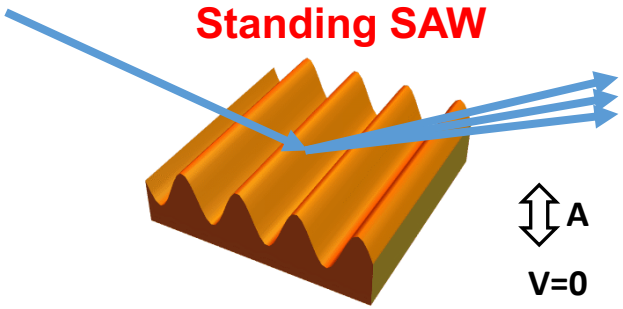
No SAW

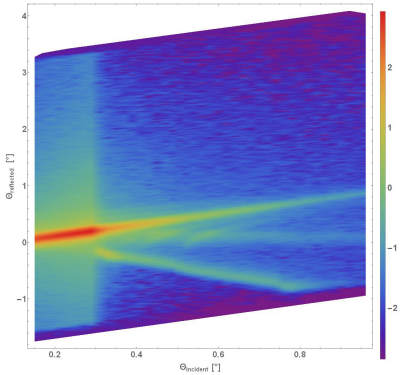


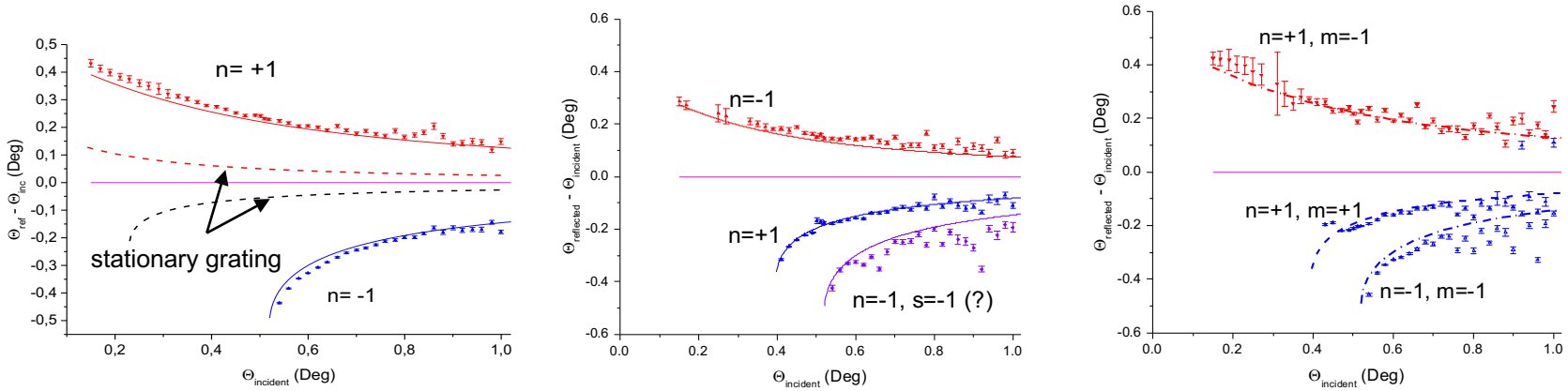




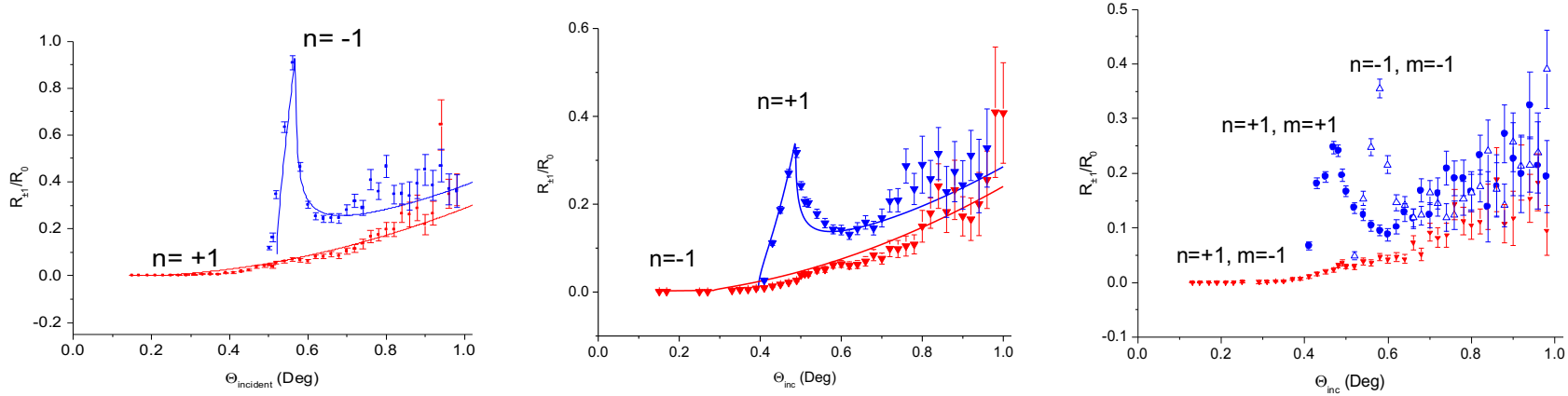








Kinematics is in good agreement with the calculations



The reflection coefficients of the corresponding diffraction orders are consistent with the SAW amplitude ~ 2 nm

Diffraction pattern in case of standing SAW looks if it is formed on two travelling waves independently

Are there any experimental results?

	Type of experiment	E, eV	Acceleration, m/sec^2	Critical accel., m/sec^2	Reference
1.	Reflection from surface acoustic waves	2.8×10^{-4} 6.7×10^{-4}	**6.3×10^{7}**	**2×10^{9}** **4.8×10^{9}**	W.A.Hamilton, A.G. Klein, G.I. Opat, P.A. Timmins, 1987
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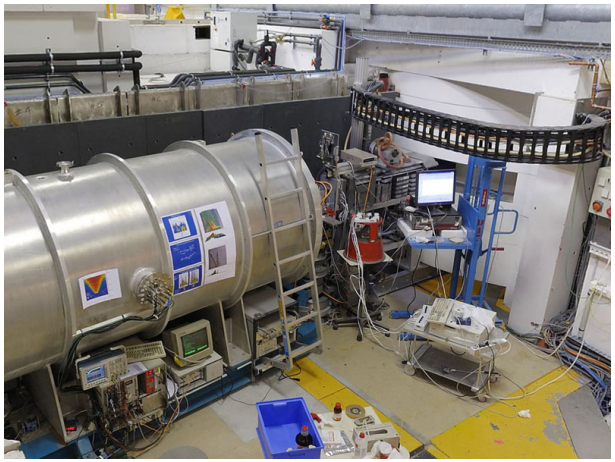
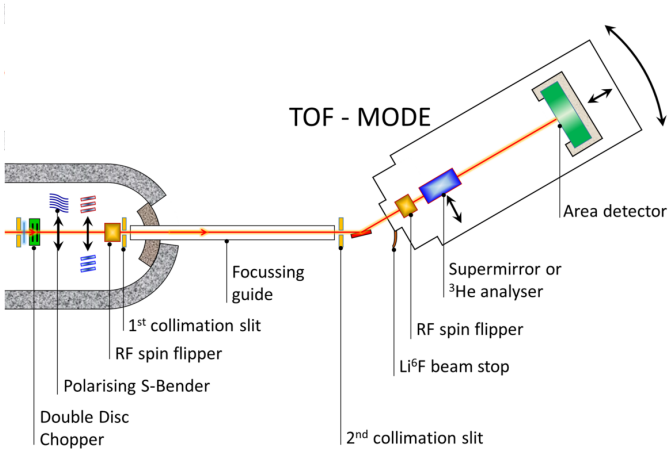
There are no contradictions with hypothesis of critical acceleration

Two experimental ways with SAW:

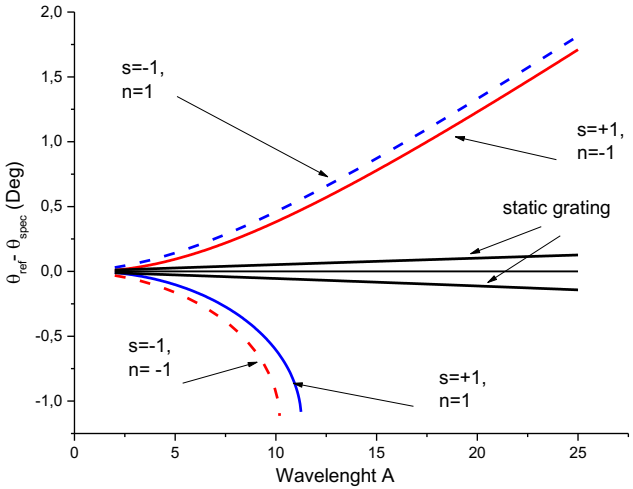
- ***Reflectometric experiment in a wide band of wavelengths***

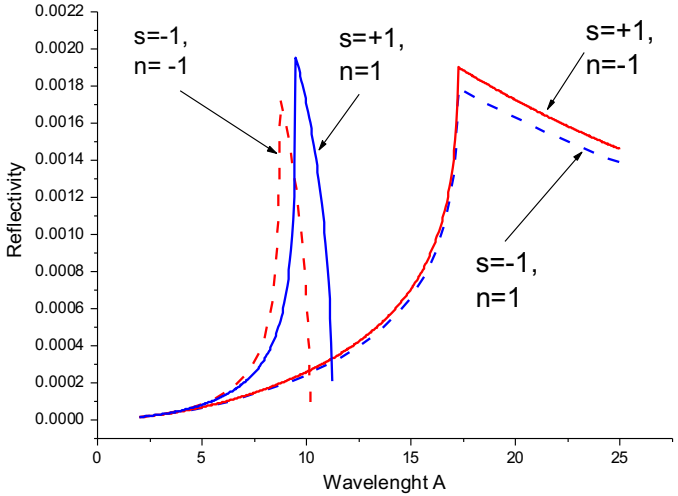
Accepted proposal to D17 reflectometer (@ILL, Grenoble France) – Autumn 2019





TOF mode measurements at number of fixed GSE for wide range of wavelength



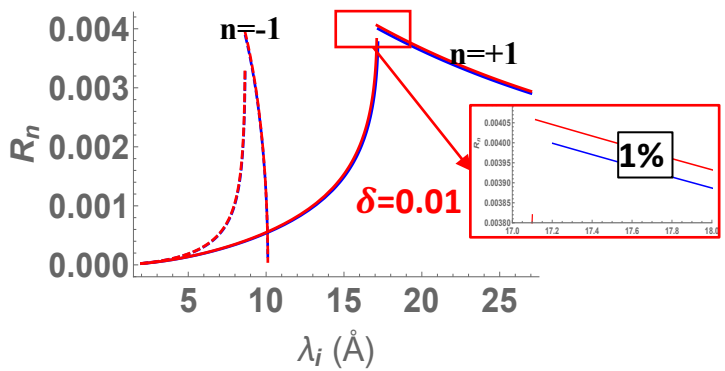


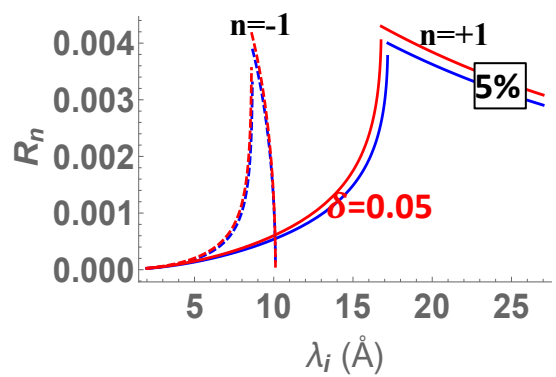
Intensities of +/-1 diffraction orders: $R_{\pm 1} = k_{0z} k_{\pm 1 z} a^2 \left| \frac{k_{0z} - q_{0z}}{k_{0z} + q_{1z}} \right|^2$,

$q_{nz} = \sqrt{k_{nz}^2 - k_b^2}$ **neutron wave number in a matter,** $k_b = \sqrt{2MU_0} / \hbar$ **critical wave number**

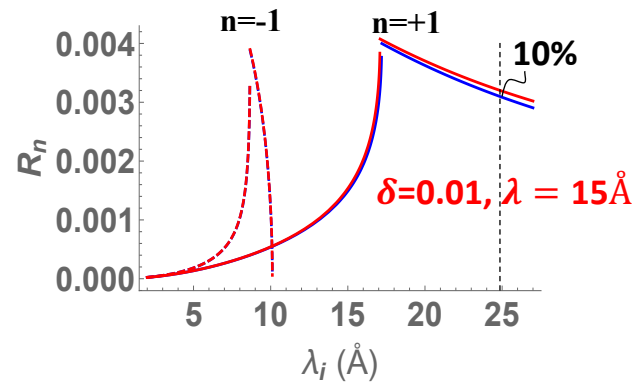
No predictions for possible deviation term

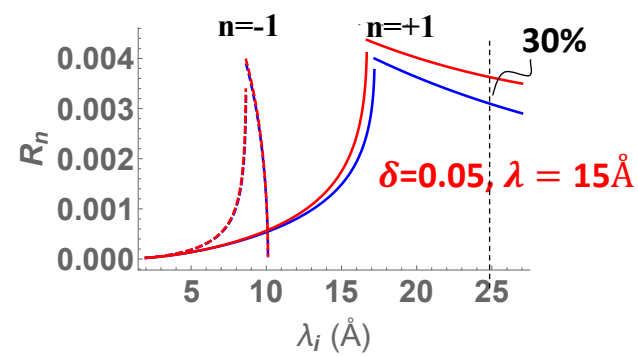
$$q_{nz}^2 = k_{nz}^2 - (1+\delta)\, k_b^2$$





$$q_{nz}^2 = k_{nz}^2 - k_b^2 - \delta\, \varepsilon(k_0^2), \quad \varepsilon(k_0^2) \sim 1/k_0^2$$





Are there any experimental results?

	Type of experiment	E, eV	Acceleration, m/sec^2	Critical accel., m/sec^2	Reference
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There are no contradictions with hypothesis of critical acceleration

Two experimental ways with SAW:

- ***Reflectometric experiment in a wide band of wavelengths***
- ***Use neutrons with an energy at which acceleration of the matter is larger the critical one***

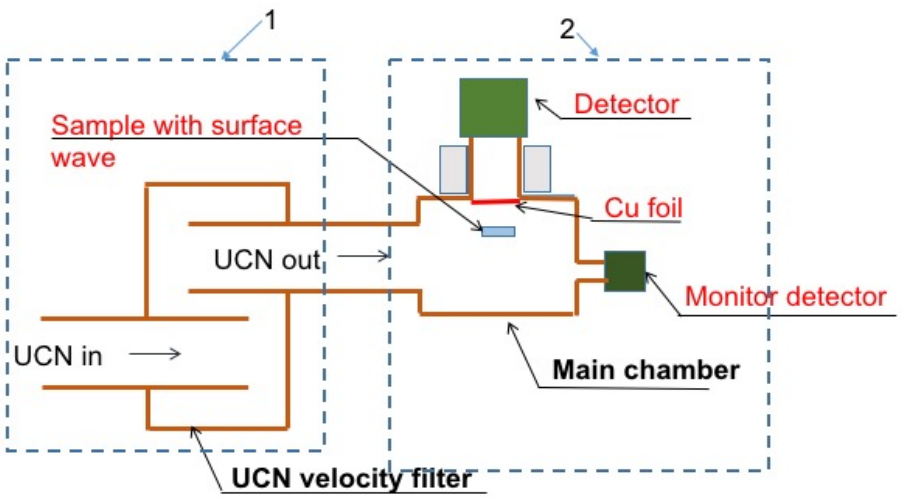
Experiment on UCN upscattering at travelling SAW

Single crystal Lithium Niobate ($LiNbO_3$):

SAW frequency: 34 MHz
SAW amplitude: ~ 2 nm

$$A\Omega^2 \approx 10^8 \text{ m/sec}^2 \text{ (SAW)},$$

$$w_{crit} = 4\times10^5 \text{ m/sec}^2 - \text{UCN } (E = 10^{-7} \text{ eV})$$



In details: S.V. Goryunov — next talk

Summary

- SAWs arise due to periodical oscillation of the near-surface layer of matter that moves with alternative velocity and acceleration

- Measurements with SAW for wide range of neutron wavelength can be suitable for the test of the concept of effective potential in case of giant acceleration.

- Existing experimental results are in agreement with potential dispersion law but there are no contradictions with hypothesis of critical acceleration

- It is planned to perform TOF mode measurements at fixed GSE for wide range of wavelength

- Experiment on UCN upscattering at SAW was started

Thank you for your attention!