Neutron Whispering Gallery and search for a 5th force

V.Nesvizhevsky, …., A.Voronin, ….

Axion

$$L_\theta = \theta_{eff} \frac{\alpha}{8\pi} F^{ijk} \overline{F}_{ij}^{k}$$

CP violating terms

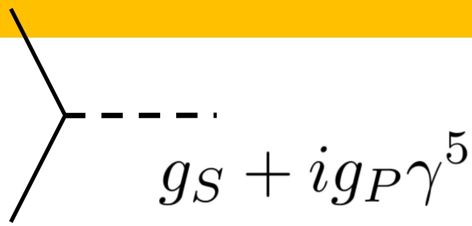
$$\theta_{eff} < 10^{-10} \longrightarrow \theta_{eff} = 0$$

New Pseudo Scalar Field (axion) , which has a vacuum minimum

WEAK interaction with matter Dark Matter Candidate

R. D. Peccei and H. R. Quinn, CP Conservation in the Presence of Pseudoparticles, Phys. Rev. Lett. 38, 1440 (1977).
[7] S.Weinberg, A New Light Boson?, Phys. Rev. Lett. 40, 223 (1978).

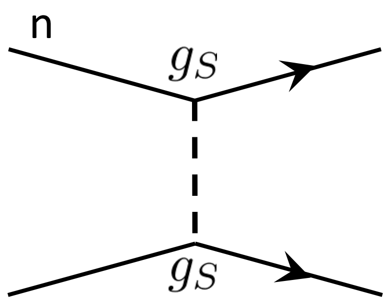
Short-range spin-dependent forces



interactions of range λ
mediated by new light boson of mass M

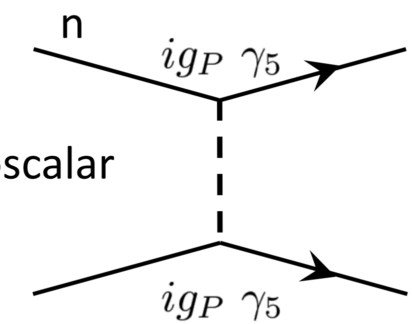
$$\lambda = \frac{\hbar}{Mc}$$

Scalar-scalar



$+$

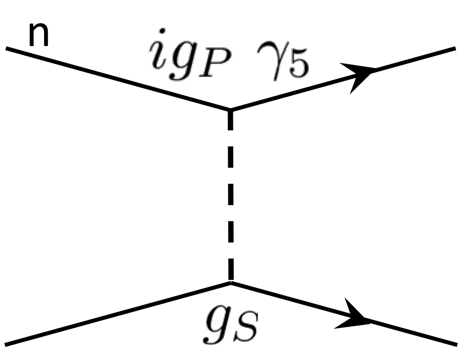
PseudoScalar-Pseudoscalar



$$1 \mu eV < M < 1 eV$$

Dipole
(probe)

$+$



Monopole
(source)

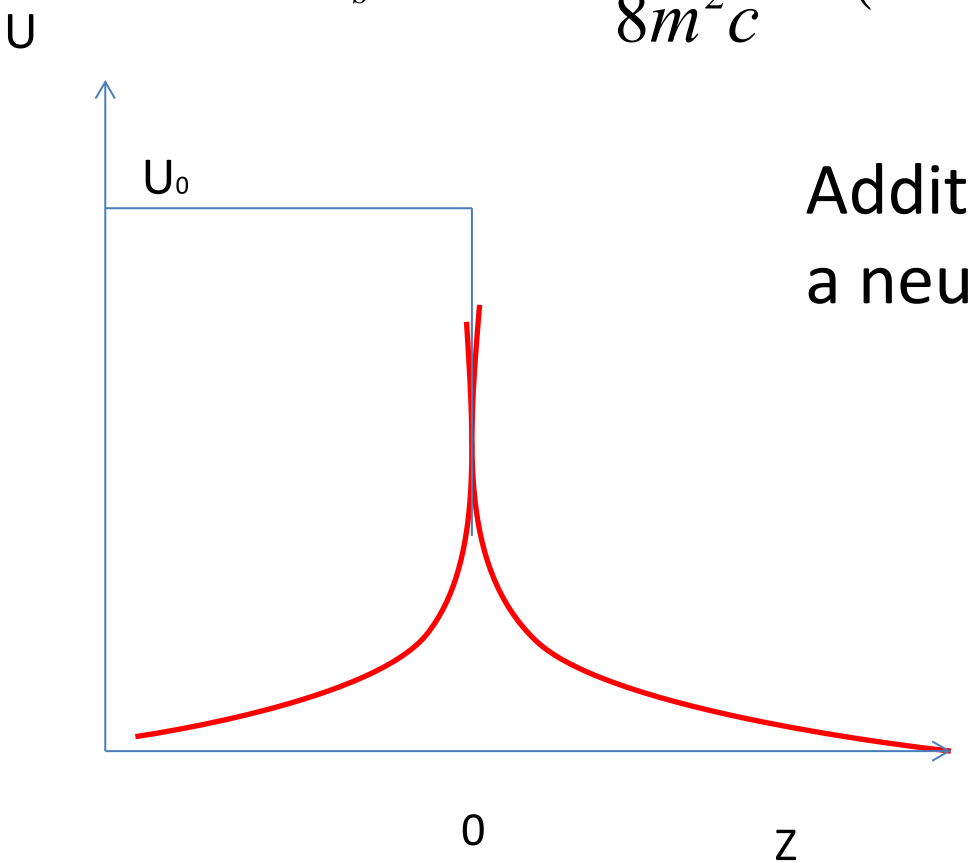
~~P~~ ~~CP~~ Scalar–Pseudoscalar (Axion–like)

$$V_{SP}(\mathbf{r}) = \frac{g_S g_P}{8\pi} \frac{\hbar}{m} \sigma \cdot \mathbf{r} \left(\frac{1}{\lambda} + \frac{1}{r} \right) \frac{e^{-r/\lambda}}{r^2}$$

Pavel Fadeev, et al PHYSICAL REVIEW A 99, 022113 (2019)

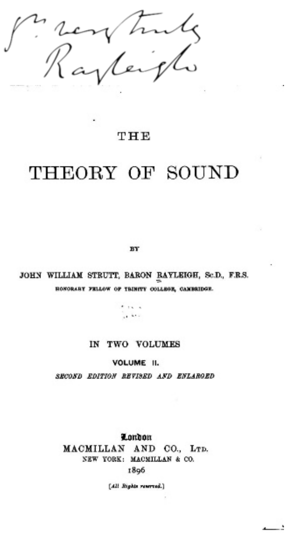
Macroscopic spin-dependent potential due to 5-th force

$$V_s(z) = \frac{g_p g_s \hbar \rho_m \lambda}{8m^2 c}\left(\vec{\sigma}\,\vec{\mathrm{n}}\right)\exp(-z/\lambda)$$



Additional interaction between a neutron and a material wall

First observation of neutron WG effect


THE

THEORY OF SOUND

BY

JOHN WILLIAM STRUTT, BARON RAYLEIGH, Sc.D., F.R.S.

HONORARY FELLOW OF TRINITY COLLEGE, CAMBRIDGE.

IN TWO VOLUMES

VOLUME II.

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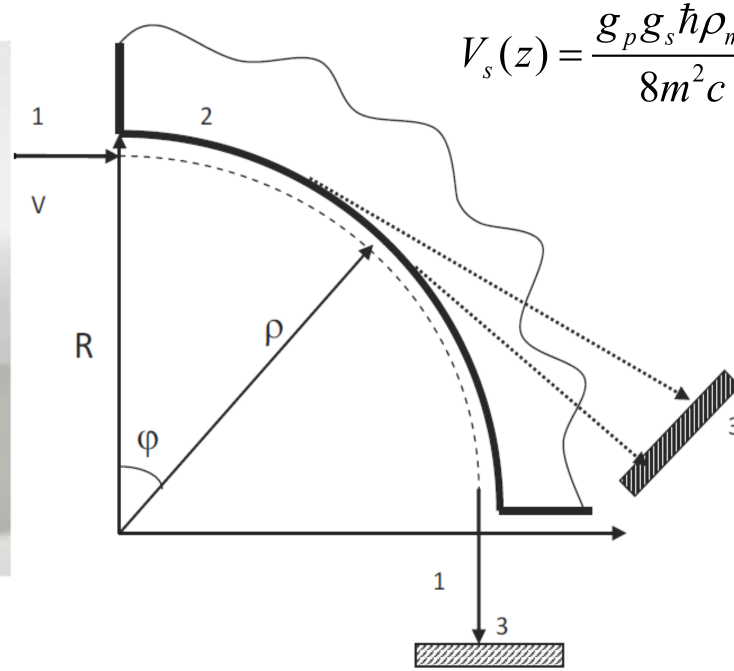


$$V_s(z) = \frac{g_p g_s \hbar \rho_m \lambda}{8m^2 c} (\vec{\sigma}\,\vec{\mathrm{n}}) \exp(-z/\lambda)$$

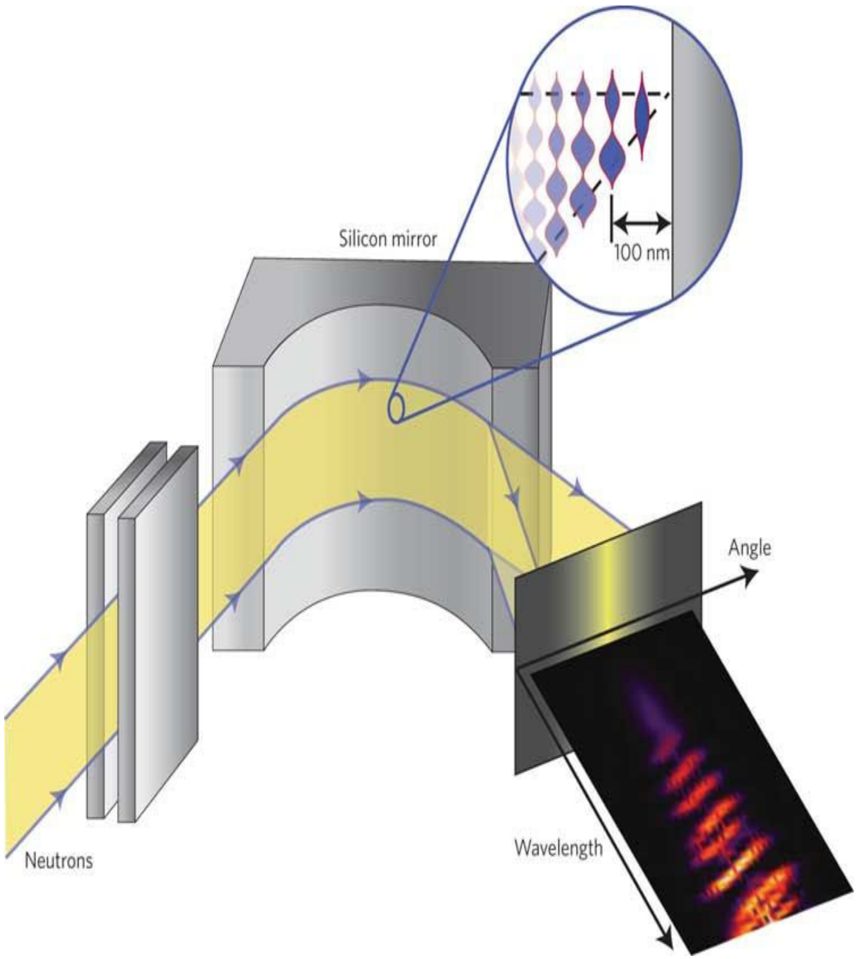
1- neutron classical trajectories, 2- cylindrical mirror, 3-detector

V.V. Nesvizhevsky, A. Voronin, R.Cubitt and K.V. Protasov (2010)

"**Neutron whispering gallery**"

Nature Physics 6:114-117

Experiment scheme

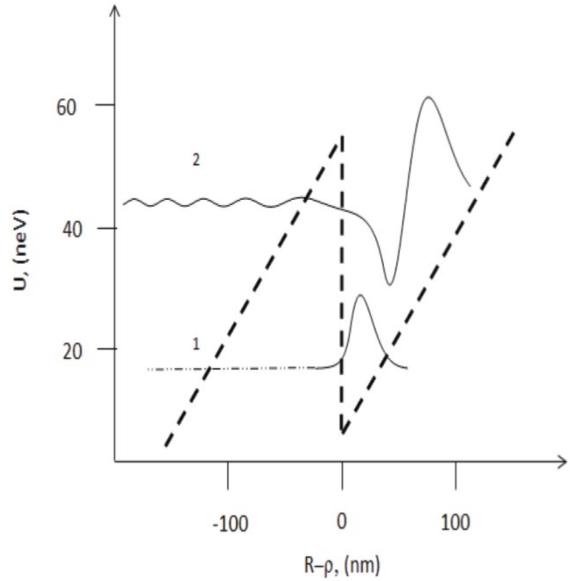


Whispering gallery states

$$\left[-\frac{1}{2M}\frac{\partial^2}{\partial z^2} - U_0\Theta(z) - \frac{Mv^2}{R}z - \varepsilon_\mu\right]\chi_\mu(z) = 0$$

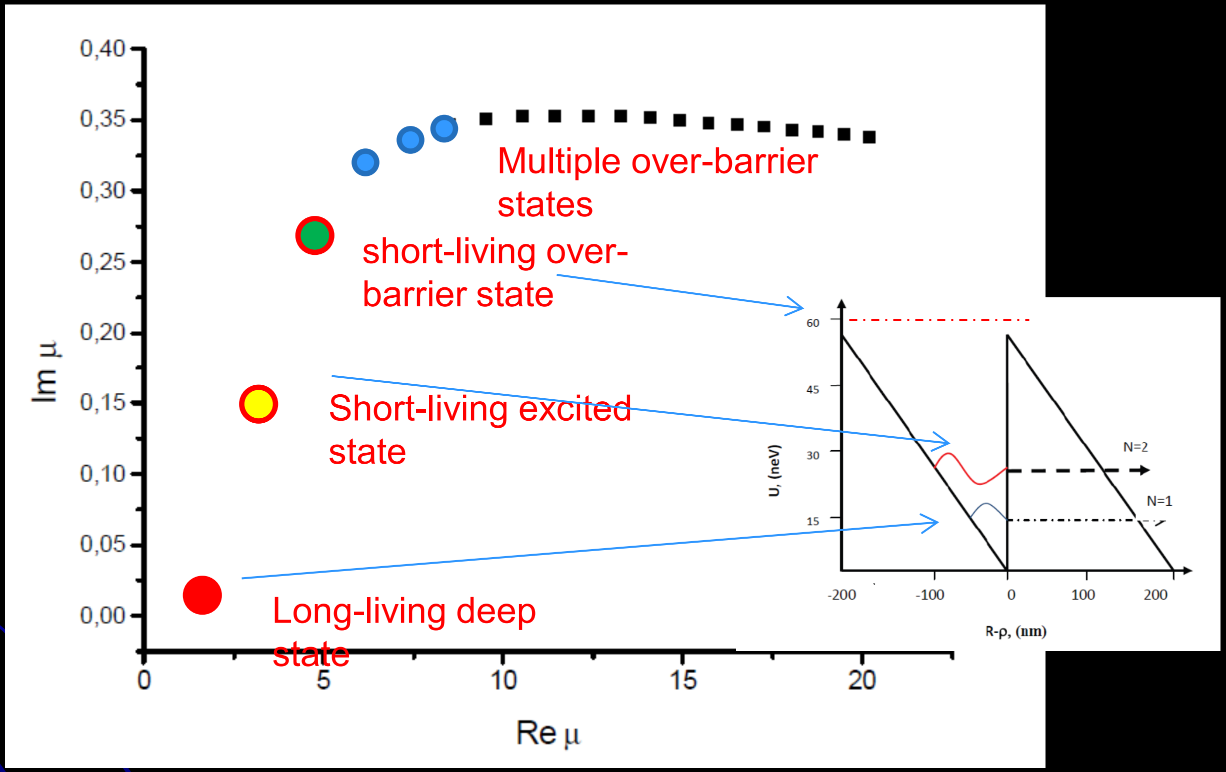
$$\varepsilon_\mu = E - \frac{(\mu^2 - 1/4)}{MR^2}$$

$$l_0 = \left(\frac{\hbar^2 R}{2M^2 v^2}\right)^{1/3} \approx 40\ \text{nm} \quad \varepsilon_0 = \left(\frac{\hbar^2 M v^4}{2R^2}\right)^{1/3} \approx 15\text{neV} \quad g_{eff} = \frac{v^2}{R} \sim 10^7 g$$



Regge Poles in Neutron Scattering by a Cylinder
Adv.High Energy Phys. 2014 (2014) 124592
K.V. Protasov A.Y. Voronin

Regge poles



0,40
0,35
0,30
0,25
0,20
0,15
0,10
0,05
0,00
Im μ
0
5
10
15
20
Re μ
Multiple over-barrier states
short-living over-barrier state
Short-living excited state
Long-living deep state
60
45
30
15
U, (neV)
-200
-100
0
100
200
R-ρ, (nm)
N=2
N=1

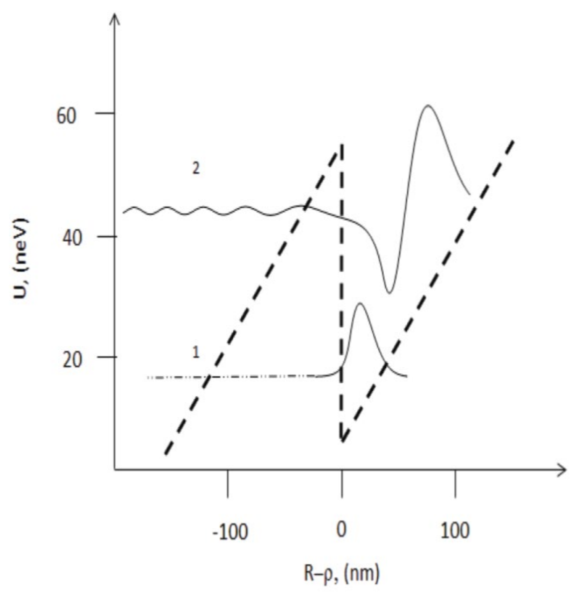
Whispering gallery states

$$\Psi(k_\varphi,\varphi)=\sum_i C_i < k_0 \mid \chi_i > e^{-i\mu_i\varphi} < \chi_i \mid k_\varphi >$$

$$C_i=\frac{1}{z_0\mathrm{Ai}^2(-\lambda_i)} \qquad \chi_i \sim \mathrm{Ai}(z-\lambda_i)$$

$$z_0=U_0/\varepsilon_0;\ \lambda_i=\left(E-\frac{\hbar^2\mu_i^2}{2MR^2}\right)/\varepsilon_0$$

$$\varepsilon_0=\left(\frac{\hbar^2Mv^4}{2R^2}\right)^{1/3}$$



$$l_0=\left(\frac{\hbar^2R}{2M^2v^2}\right)^{1/3}\approx 40\text{ nm} \quad \varepsilon_0=\left(\frac{\hbar^2Mv^4}{2R^2}\right)^{1/3}\approx 15\text{neV}\ g_{eff}=\frac{v^2}{R}\sim 10^7 g$$

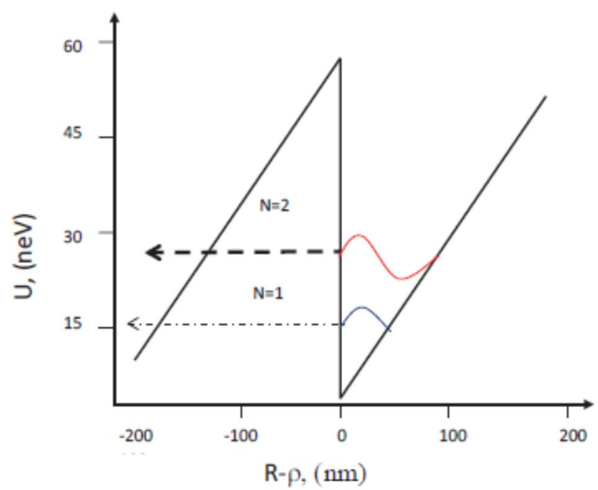
Whispering gallery states

n	Im λ	T (s)
1	$-6.4\ 10^{-25}$	$1.2\ 10^{17}$
2	$-2.4\ 10^{-18}$	$2.3\ 10^{12}$
3	$-3.6\ 10^{-9}$	$9.7\ 10^{7}$
4	$-5.7\ 10^{-7}$	$3.2\ 10^{5}$
5	$-1.3\ 10^{-5}$	803
6	$-3.7\ 10^{-3}$	0.06
7	$-4.5\ 10^{-2}$	0.001

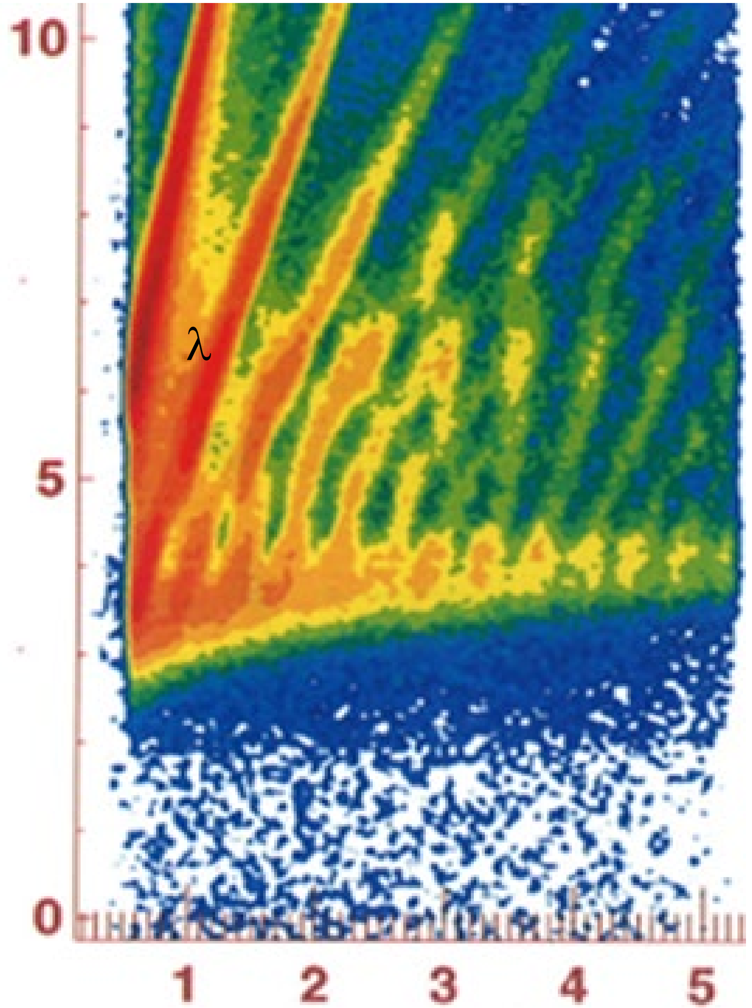
$$t_0 = \hbar / \varepsilon_0 \sim 7 * 10^{-8} s$$

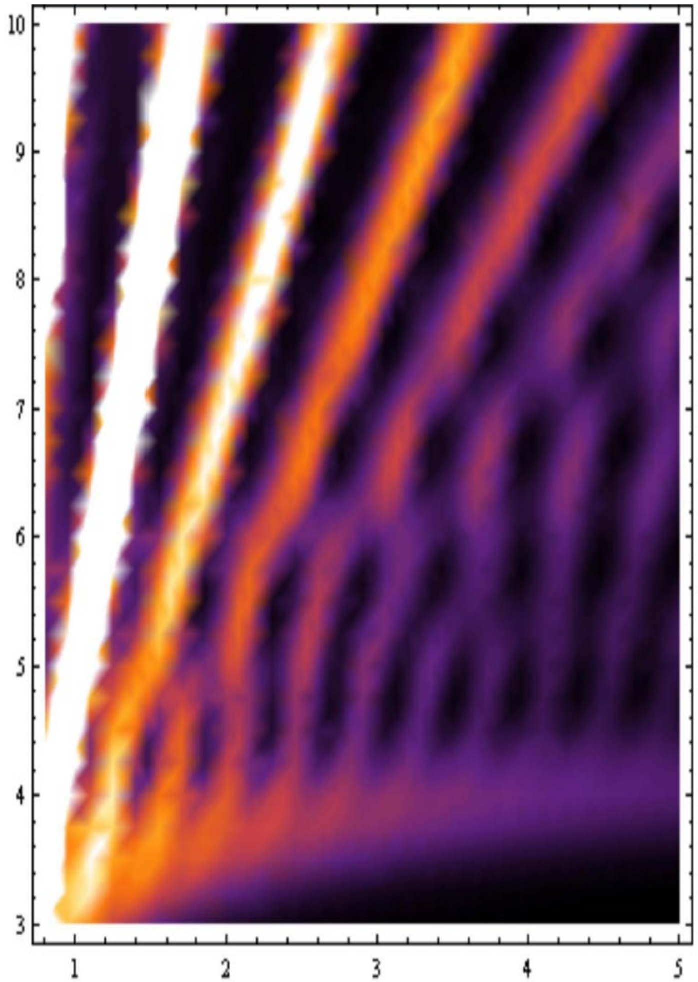
$$t_{fl} = R\varphi / v \sim 3 * 10^{-5} s$$

$$\tau_a = \frac{R\sqrt{U}}{v^2 \sqrt{M}} \frac{U}{|\operatorname{Im} U|} \sim 1s$$



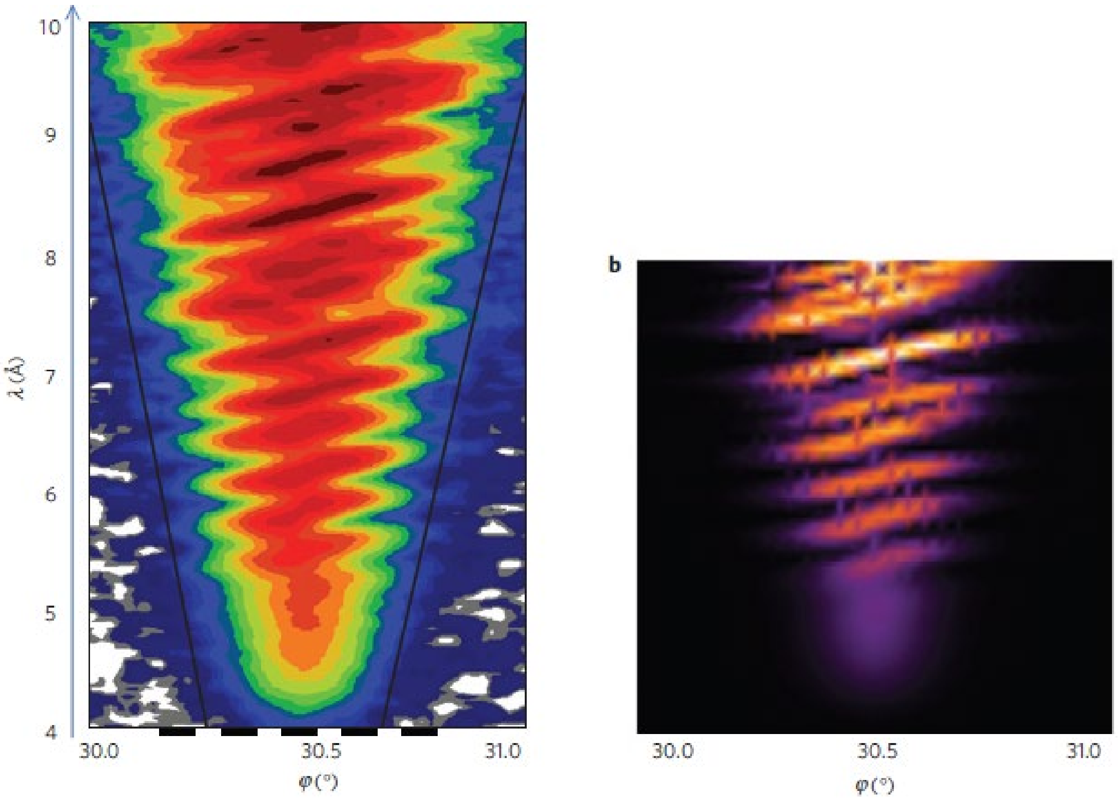
Interference of tunneling WG states





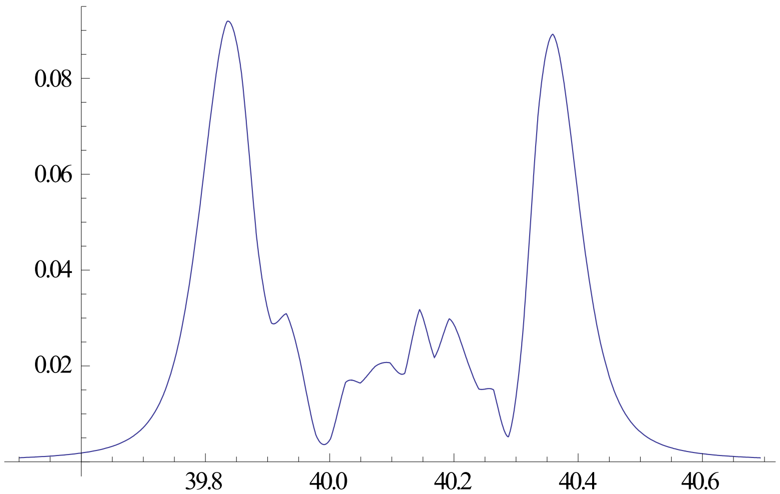
Experiment φ **Theory**

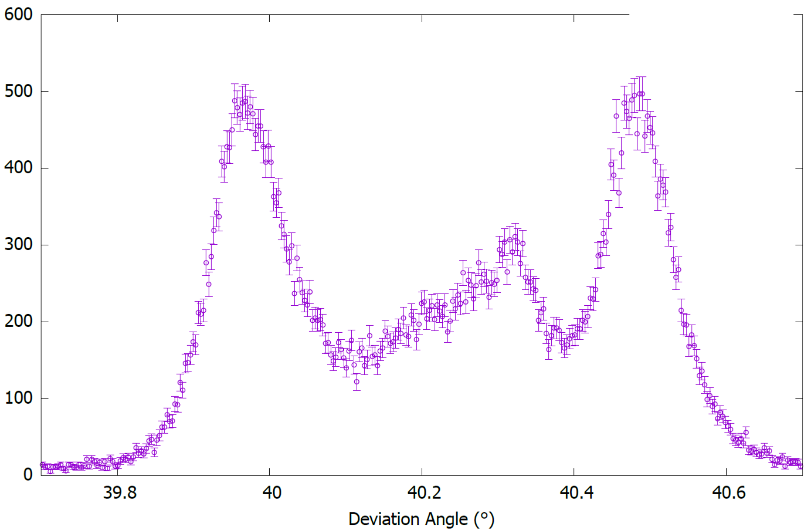
Interference of deep WG states



High sensitivity of interference pattern on details of neutron-surface interaction

Рассеяние монохроматического потока нейтронов 2019

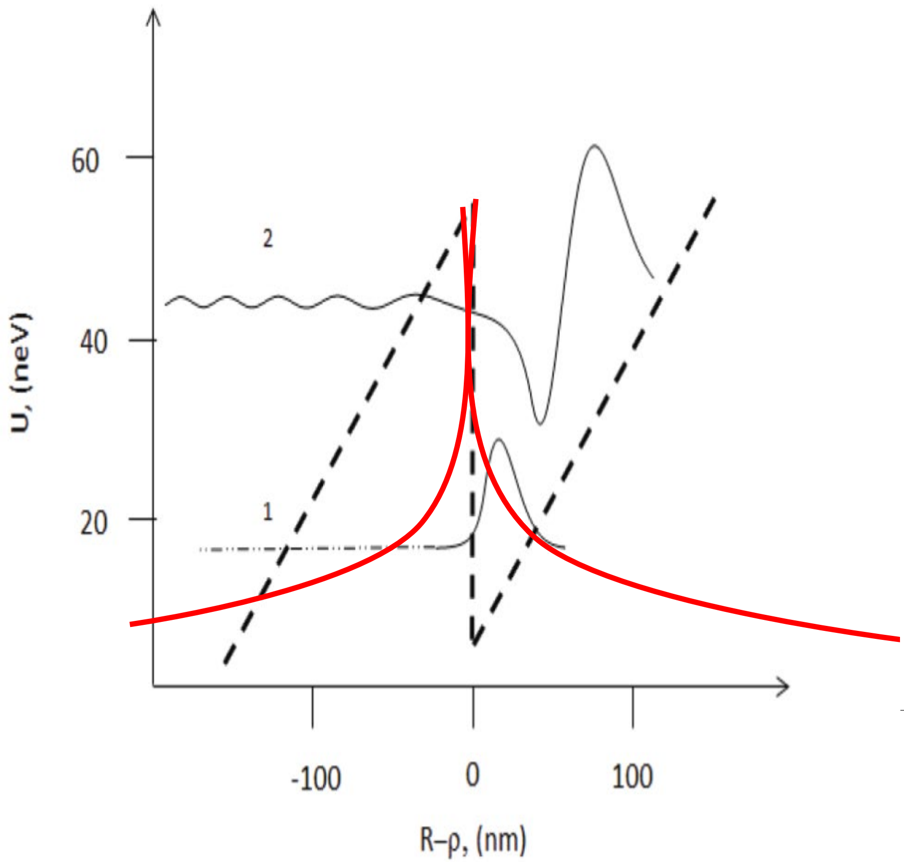


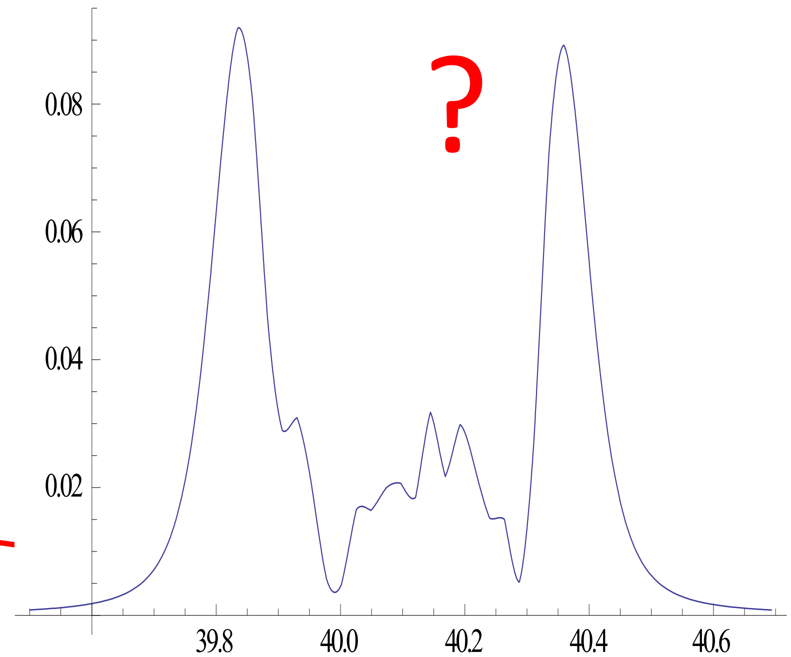


$$\lambda = 5.184 A, \quad \varphi_0 = 0.355^0$$

Macroscopic spin-dependent potential due to 5-th force

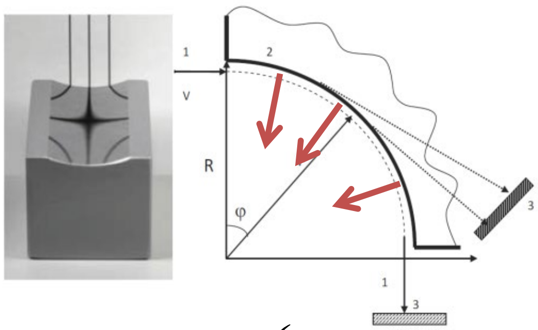
$$V_s(z) = \frac{g_p g_s \hbar \rho_m \lambda}{8m^2 c}(\vec{\sigma}\vec{\mathrm{n}})\exp(-z/\lambda)$$





Spin dynamics

$$U_5(z) = \frac{g_p g_s \hbar \rho_m \lambda}{8m^2 c}\left(\vec{\sigma}\,\vec{\mathrm{n}}\right)\exp(-z/\lambda)$$



$$\left(\hat{H}-E\right)\Phi_1(z,\varphi)+U_5(z)\exp(-i\varphi)\Phi_2(z,\varphi)=0$$

$$\left(\hat{H}-E\right)\Phi_2(z,\varphi)+U_5(z)\exp(i\varphi)\Phi_1(z,\varphi)=0$$

$$\left(\hat{H}-E-\frac{1}{2}\hbar\Omega+\mu B\right)F_1(z,\varphi)+U_5(z)F_2(z,\varphi)=0$$

$$\left(\hat{H}-E+\frac{1}{2}\hbar\Omega-\mu B\right)F_2(z,\varphi)+U_5(z)F_1(z,\varphi)=0$$

$$F_{1,2}=\Phi_{1,2}\exp(\pm i\varphi/2)\;\;\Omega=\frac{\hbar m}{MR^2}$$

Resonant spin-flip

$$B = \frac{\hbar\Omega}{2\mu} \qquad F^{\pm}(z) = \frac{1}{2}(F_1(z) \pm F_2(z))$$

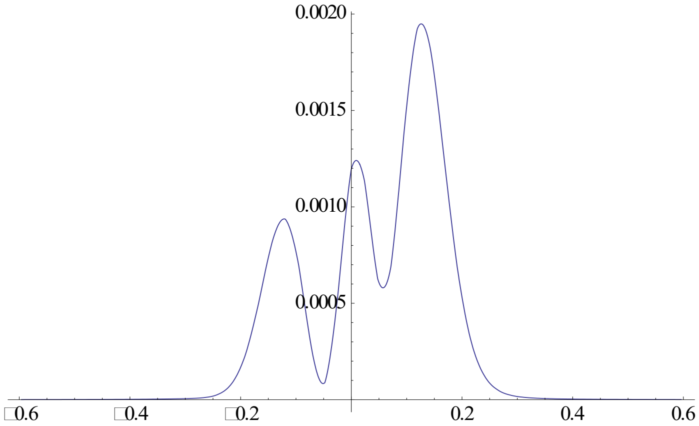
$$\left(\hat{H} + U_5(z)\right) F_i^+(z) = \varepsilon_i^+ F_i^+(z)$$

$$\left(\hat{H} - U_5(z)\right) F_i^-(z) = \varepsilon_i^- F_i^-(z)$$

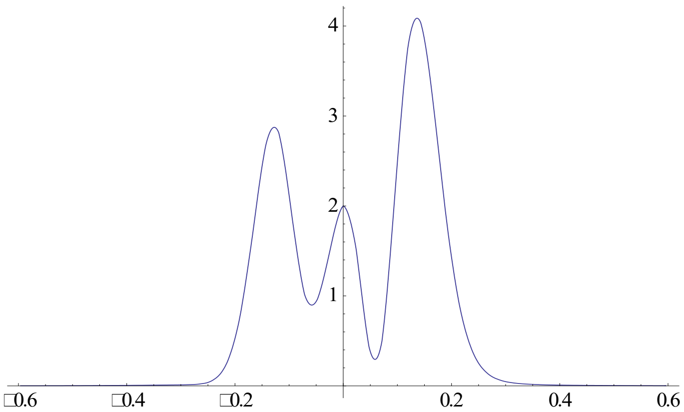
$$P(z,T) \approx \left| \sum_{i=1}^{N} < k_0 \mid \chi_i^0 > \exp(-i\varepsilon_i^0 T / \hbar) < \chi_i^0 \mid z > \sin\left[\frac{\Delta_i T}{\hbar}\right] \right|^2$$

$$\Delta = < \chi_i^0 \mid U_5 \mid \chi_i^0 >$$

Interference pattern



Spin flip



No spin flip

Ramsey type approach

Measurement of a linear effect

$$P^{+} - P^{-} \square \Delta$$

$$\left(\hat{H} - \mathrm{E} + \mu B_x + U_5(z)\cos(\varphi)\right) f_1(z) - U_5(z)\sin(\varphi) f_2(z) = 0$$

$$\left(\hat{H} - \mathrm{E} - \mu B_x - U_5(z)\cos(\varphi)\right) f_2(z) + U_5(z)\sin(\varphi) f_1(z) = 0$$

$$\left(\hat{H} - \mathrm{E} + \mu B_x + U_5(z)\cos(\varphi)\right) f_1^0(z) = 0$$

$$\left(\hat{H} - \mathrm{E} - \mu B_x - U_5(z)\cos(\varphi)\right) f_2^0(z) = 0$$

$$P^{\pm}(p,t) = \left| \sum_{i=1}^{N} < k_0 \mid \chi_i^0 > \exp(-i\varepsilon_i^0 t / \hbar) < \chi_i^0 \mid p > \sin((\Delta_i \pm \Xi)t / \hbar) \right|^2$$

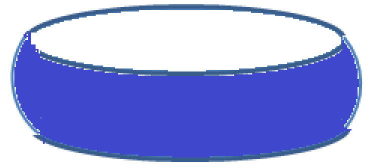
$$\Delta_i = \varepsilon_i^+ - \varepsilon_i^- = 2 < \chi_i^0 \mid U_5(z) \mid \chi_i^0 >$$

$$\Xi = 2\mu B_x$$

Effect is Linear in Δ!

Open spherical WG resonator

$$(\widehat{T_r} + \widehat{T_\theta} + \widehat{T_\varphi} + V(r) - E)F(r,\theta,\varphi) = 0$$



$$\theta = \frac{\pi}{2} - \vartheta, |\vartheta| \ll 1 \qquad z = R sin(\vartheta)$$

$$\left[-\frac{\hbar^2}{2m}\frac{d^2}{dz^2} + \frac{m}{2}\omega_z^2 z^2 - \hbar\omega_z(k+1/2)\right]\psi(z) = 0; \;\; \omega_z = \frac{\hbar\mu}{mR^2} = \frac{v}{R}$$

$$E_{n,\mu,k} = \frac{\hbar^2}{2m}\frac{l(l+1)}{R^2} + \frac{\hbar^2 l^{4/3}}{2^{1/3} mR^2}\lambda_n + \frac{\hbar^2}{m}\frac{\mu(l-\mu)}{R^2}$$

$$\Gamma_a = \frac{\hbar^2 l^2}{M^{3/2}}\frac{|\operatorname{Im} U|}{R^3 U^{3/2}}$$

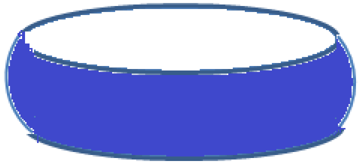
$$z_{\max} = \frac{l-\mu+1/2}{\mu} R \;\square\; R;$$

Ramsey type approach

$$\left(\hat{H} - \mathrm{E} + \mu B_x + U_5(z,\varphi)\cos(\varphi)\right) f_1(z) = 0$$

$$\left(\hat{H} - \mathrm{E} - \mu B_x - U_5(z,\varphi)\cos(\varphi)\right) f_2(z) = 0$$

$$U_5(z,\varphi) = \begin{matrix} \text{gold},\ 0<\varphi<\pi \\ \mathrm{MgF_2},\ \pi \le \varphi \le 2\pi \end{matrix} \qquad \overline{U_5(z,\varphi)\cos(\varphi)} \neq 0$$



$$P^+ - P^- \sim \Delta$$

$$\Delta_i = \varepsilon_i^+ - \varepsilon_i^- = 2 < \chi_i^0 \,|\, U_5(z) \,|\, \chi_i^0 >$$

$$\Xi = 2\mu B_x$$

Ограничения на 5 силы