Neutron quantum states in a gravitational field

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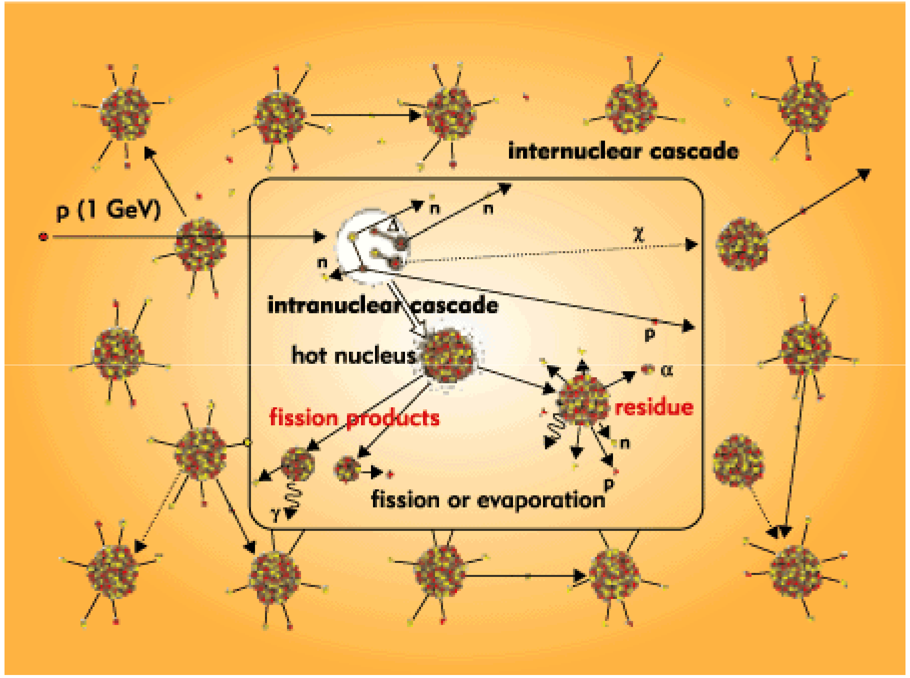
The neutron source of the ILL/Grenoble

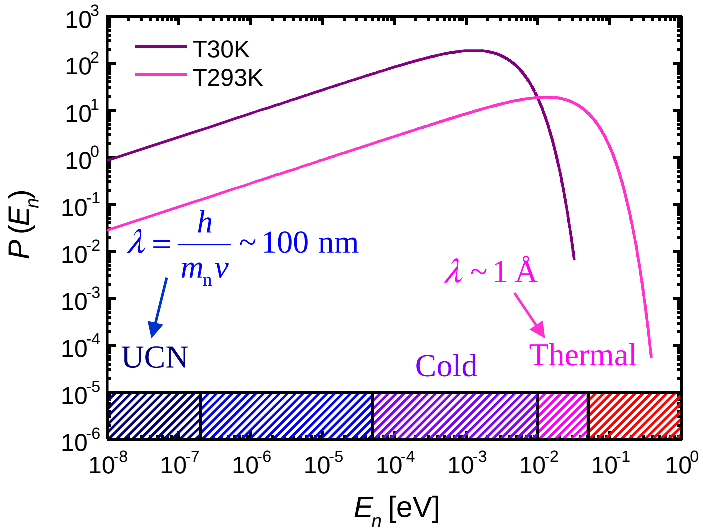
The Spallation Neutron Source SNS

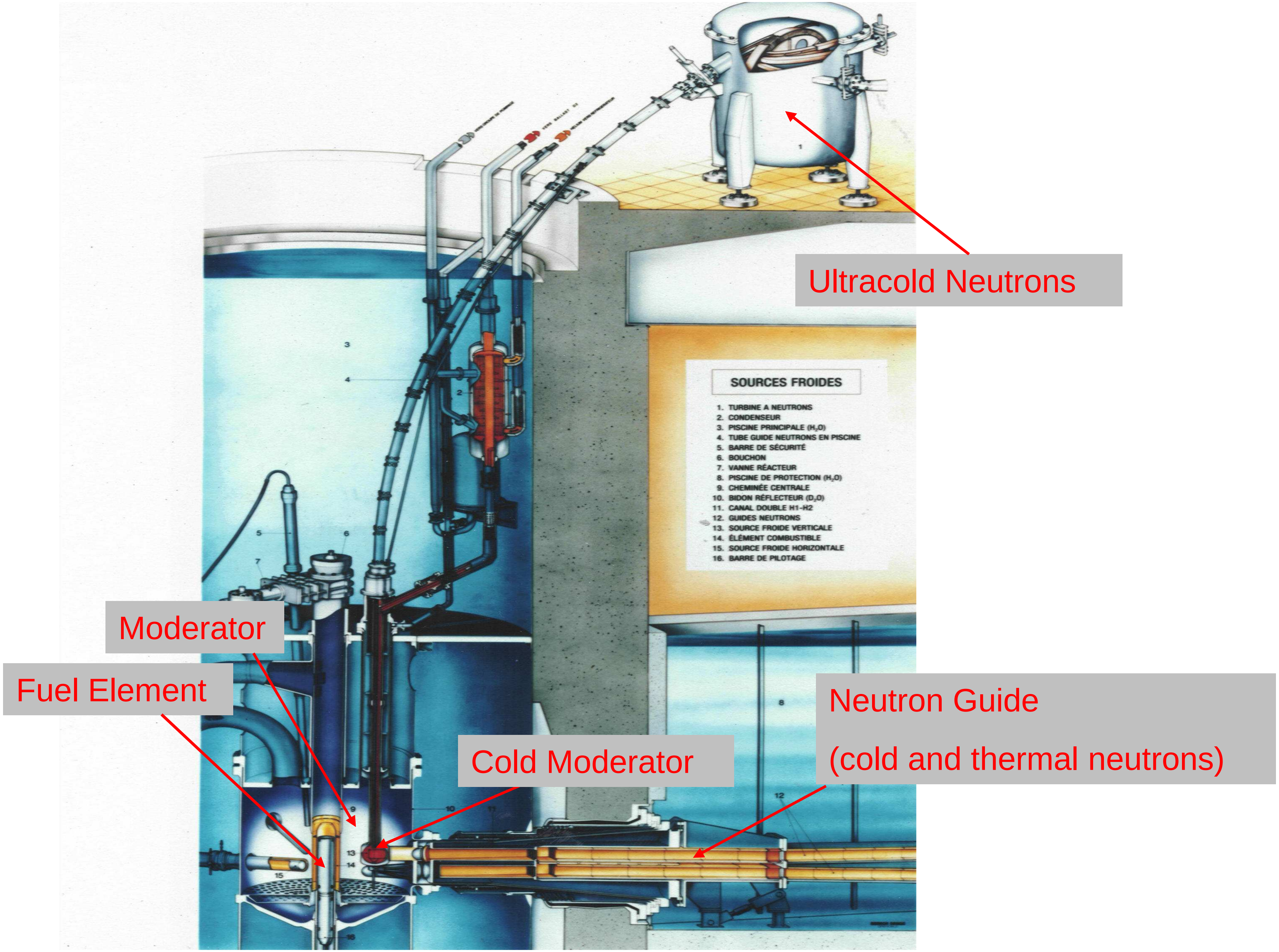
Production of free neutrons



Neutron production in a spallation source

Neutron moderation




Ultracold Neutrons
SOURCES FROIDES
1. TURBINE A NEUTRONS
2. CONDENSEUR
3. PISCINE PRINCIPALE (H_2O)
4. TUBE GUIDE NEUTRONS EN PISCINE
5. BARRE DE SÉCURITÉ
6. BOUCHON
7. VANNE RÉACTEUR
8. PISCINE DE PROTECTION (H_2O)
9. CHEMINÉE CENTRALE
10. BIDON RÉFLECTEUR (D_2O)
11. CANAL DOUBLE H1-H2
12. GUIDES NEUTRONS
13. SOURCE FROIDE VERTICALE
14. ÉLÉMENT COMBUSTIBLE
15. SOURCE FROIDE HORIZONTALE
16. BARRE DE PILOTAGE
Moderator
Fuel Element
Cold Moderator
Neutron Guide
(cold and thermal neutrons)

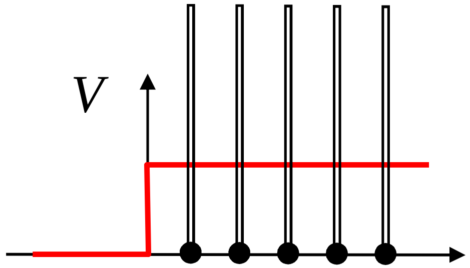
Interactions of low energy neutrons with matter

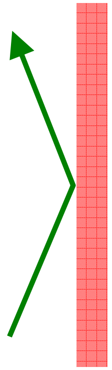
Transport

$$V_{\mathrm{Fermi}} = \frac{2\pi\hbar^2}{m_{\mathrm{n}}} \sum_i b_i \delta(x - x_i)$$

$$\lambda \text{ big:} \quad V_{\mathrm{Fermi}} \approx \frac{2\pi\hbar^2}{m_{\mathrm{n}}} \langle nb \rangle$$

~ 100 neV

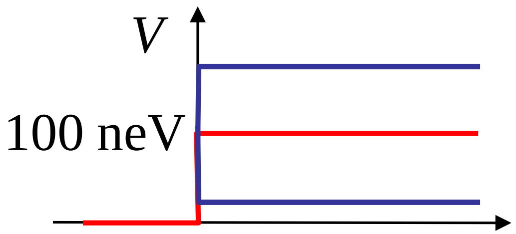


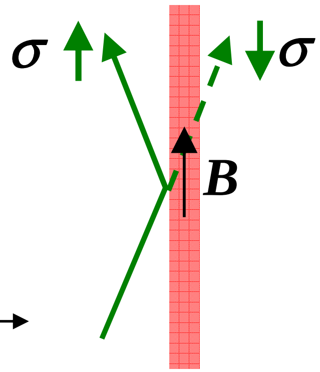


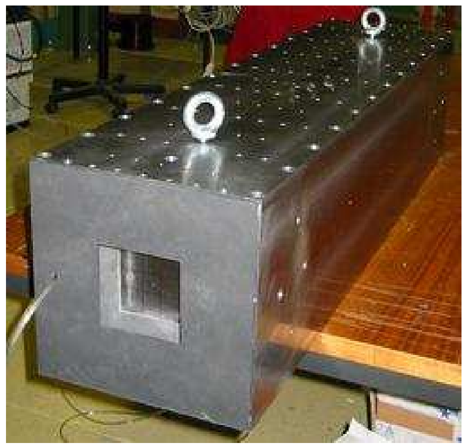
Polarization

$$V = V_{\mathrm{Fermi}} \mp \boldsymbol{\mu}_{\mathrm{n}} \boldsymbol{B}$$

100 neV   100 neV







Properties of Ultracold Neutrons (UCN)

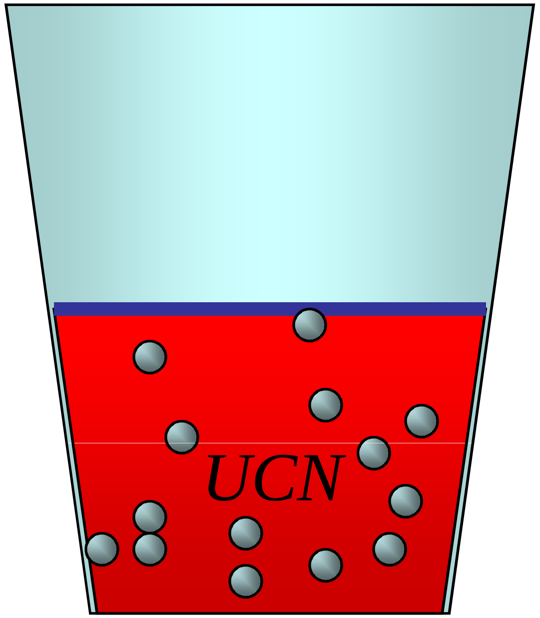
Ultracold neutrons (UCN): Neutrons with energies less than the Fermi potential of a given piece of matter.

Typical properties:

Energy: $E_{\mathrm{UCN}} \sim 100$ neV

Velocity: $v_{\mathrm{UCN}} \sim 5$ m/s

Height: $h_{\mathrm{UCN}} \sim 1$ m



Main usage: Precise fundamental physics

- Neutron lifetime
- Electric Dipole Moment and other EM moments
- Gravitation

Typical wall interaction rates for *good* walls:

~99.99 % - elastic reflection

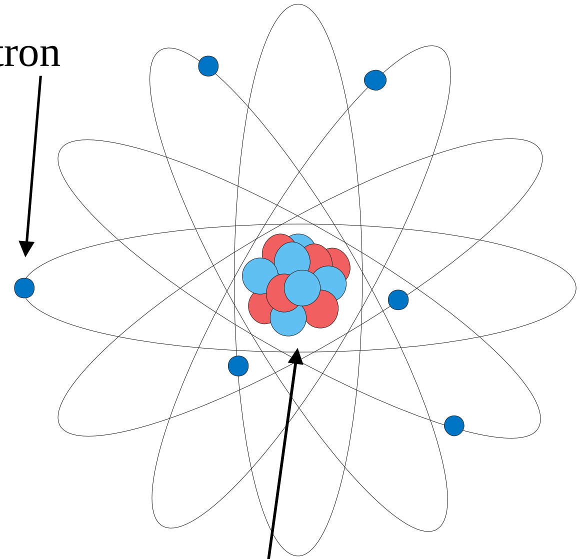
~0.01% - inelastic scattering (phonon absorption) to the thermal energy range

0.001% - absorption

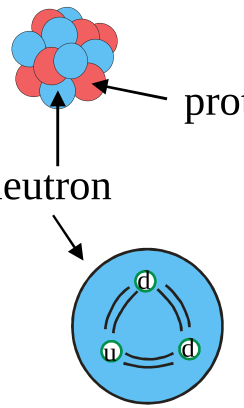
Experiment: Gravitational Bound States

Electromagnetic Bound State

electron



Strong Interaction Bound States

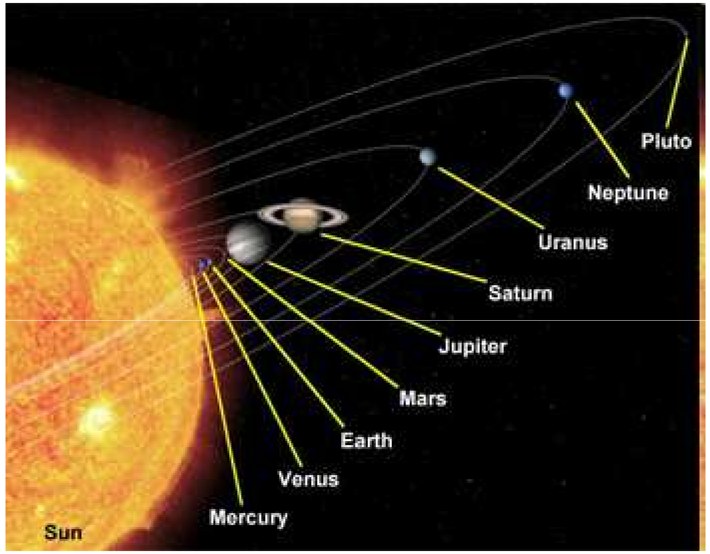


Nucleus (^{12}C)

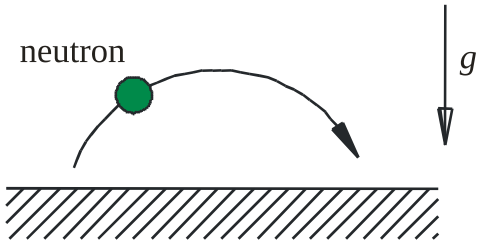
proton

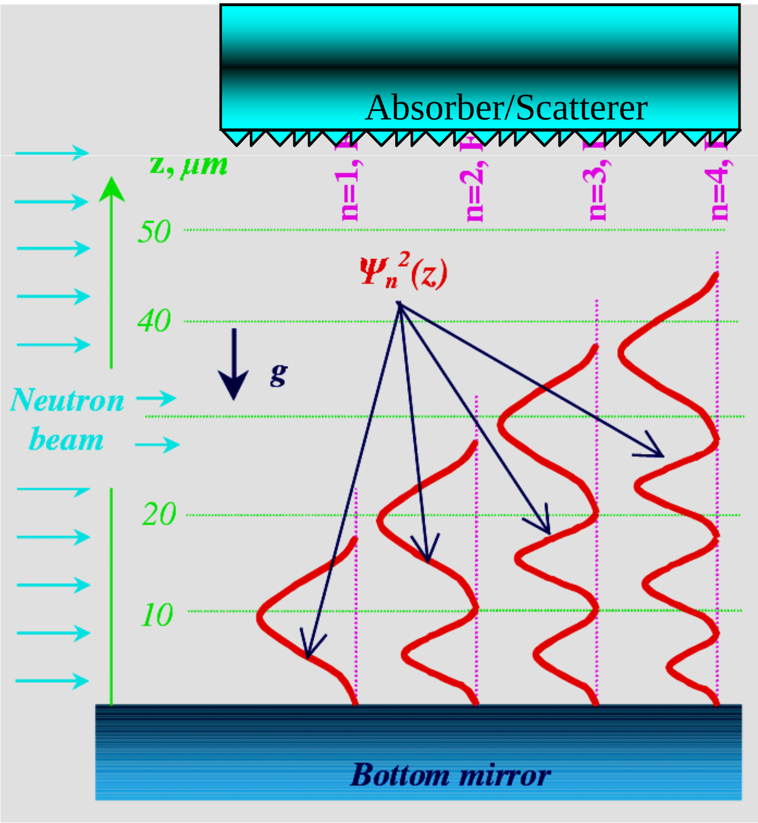
neutron

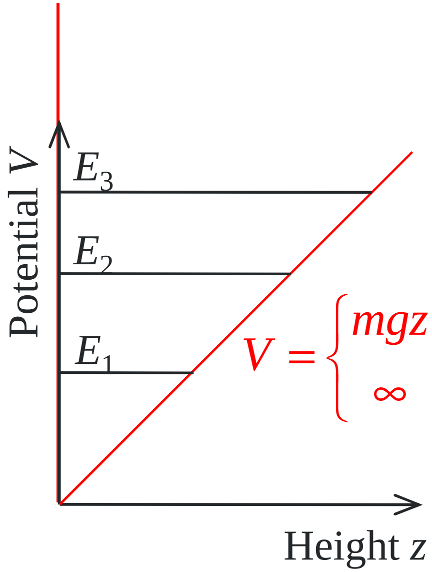
Gravitational Bound State



Gravitational Bound states – The idea





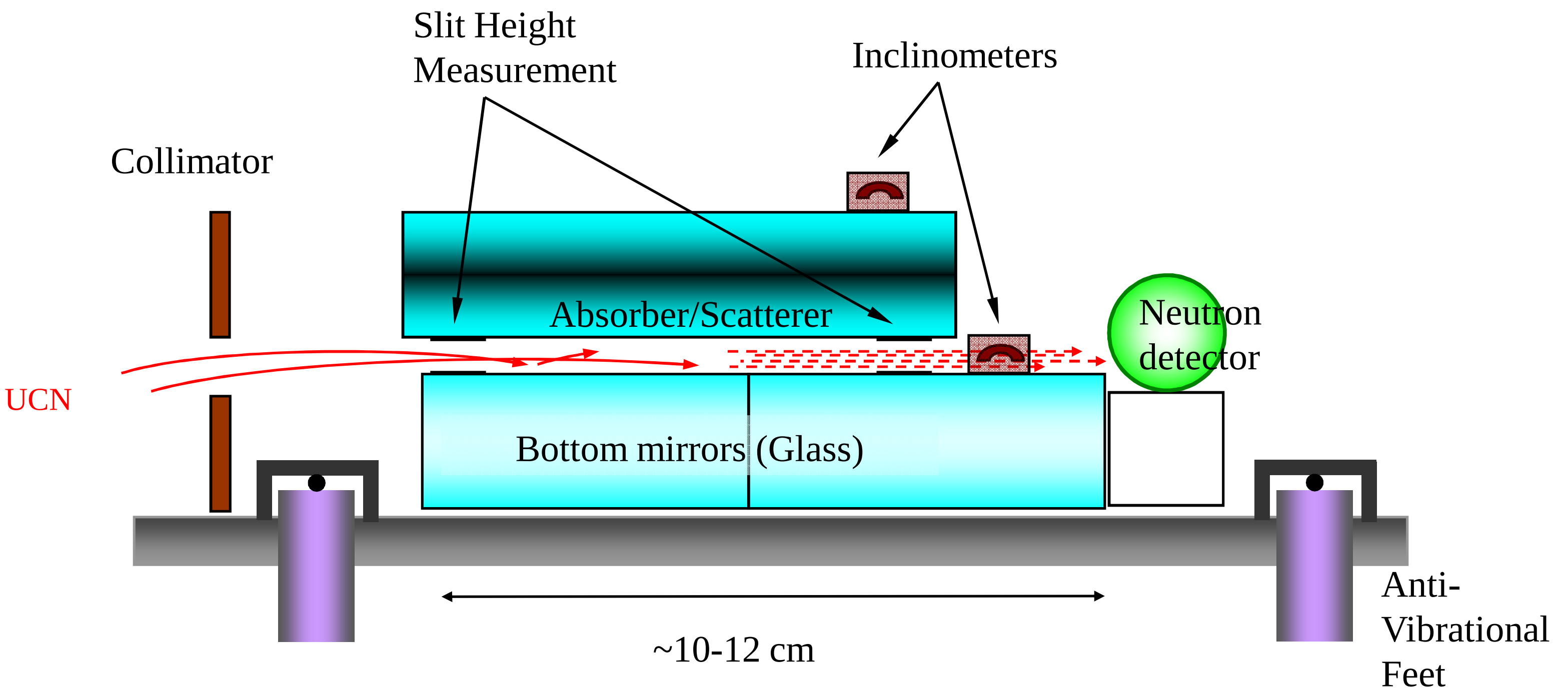


$$V = \begin{cases} mgz & ; z > 0 \\ \infty & ; \text{otherwise} \end{cases}$$

Early proposals:

- Neutrons: V.I. Lushikov (1977/78), A.I. Frank (1978)
- Atoms: H. Wallis et al. (1992)

Gravitational Bound States – The experiment



UCN selected with very small (vertical) energy:

- Effective (vertical) temperature of neutrons is ~20 nK, horizontal temperature is 10 mK
- Horizontal velocity spectrum: 4..9 m/s

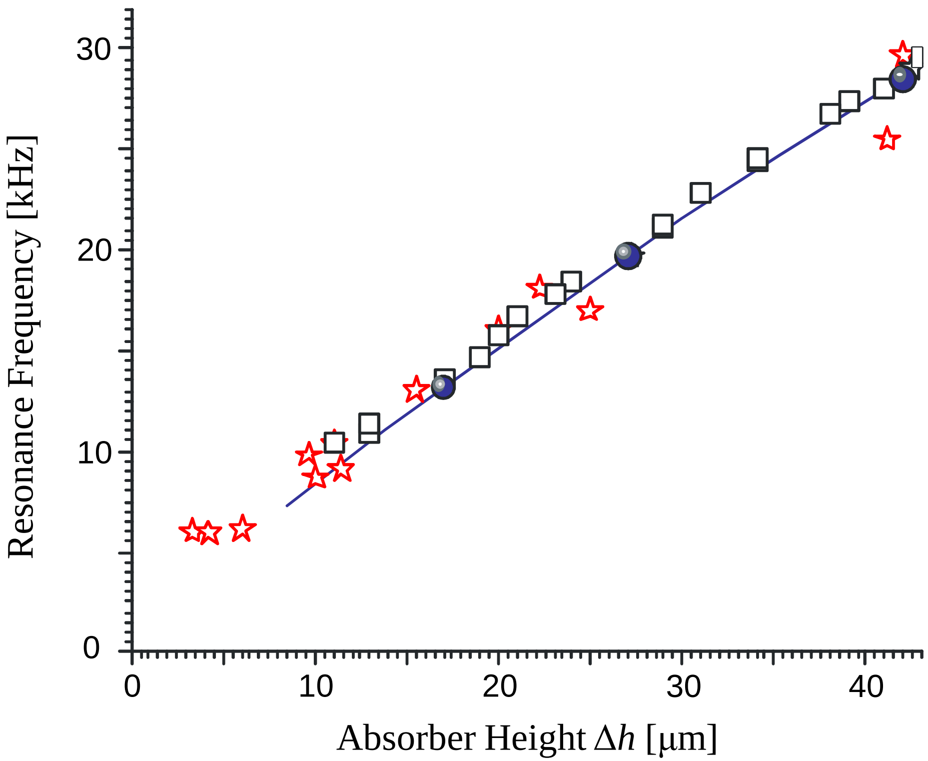
Control of geometry:

- Parallelism of the bottom mirror and the absorber/scatterer is ~ μrad
- Accuracy of absorber height determination is ideally < 0.5 μm

Efficient detection necessary:

- Count rates at ILL turbine: ~1/s to 1/h
- Background suppression is a factor of ~10^8-10^9

Calibration of the absorber height



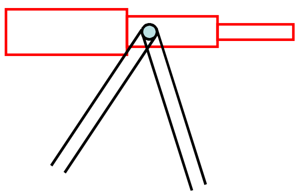
Tools:

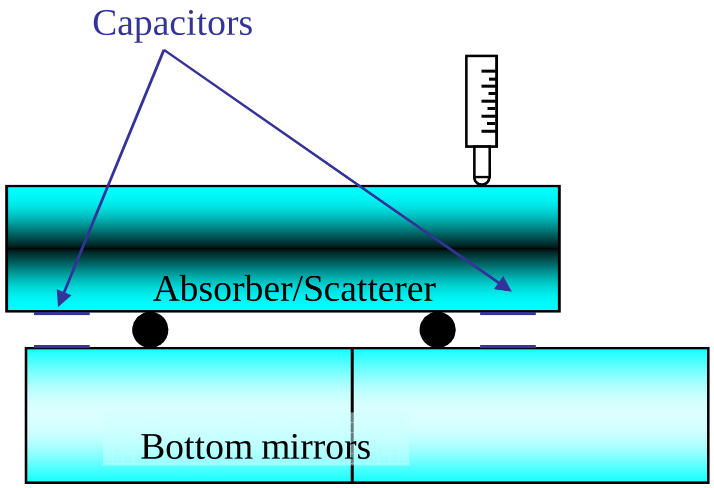
- Capacitors (To be calibrated)
- Micrometric Screw (□)
- Long-Range Microsocope (☆)
- Wire Spacers (●)

Uncertainty in Δh:

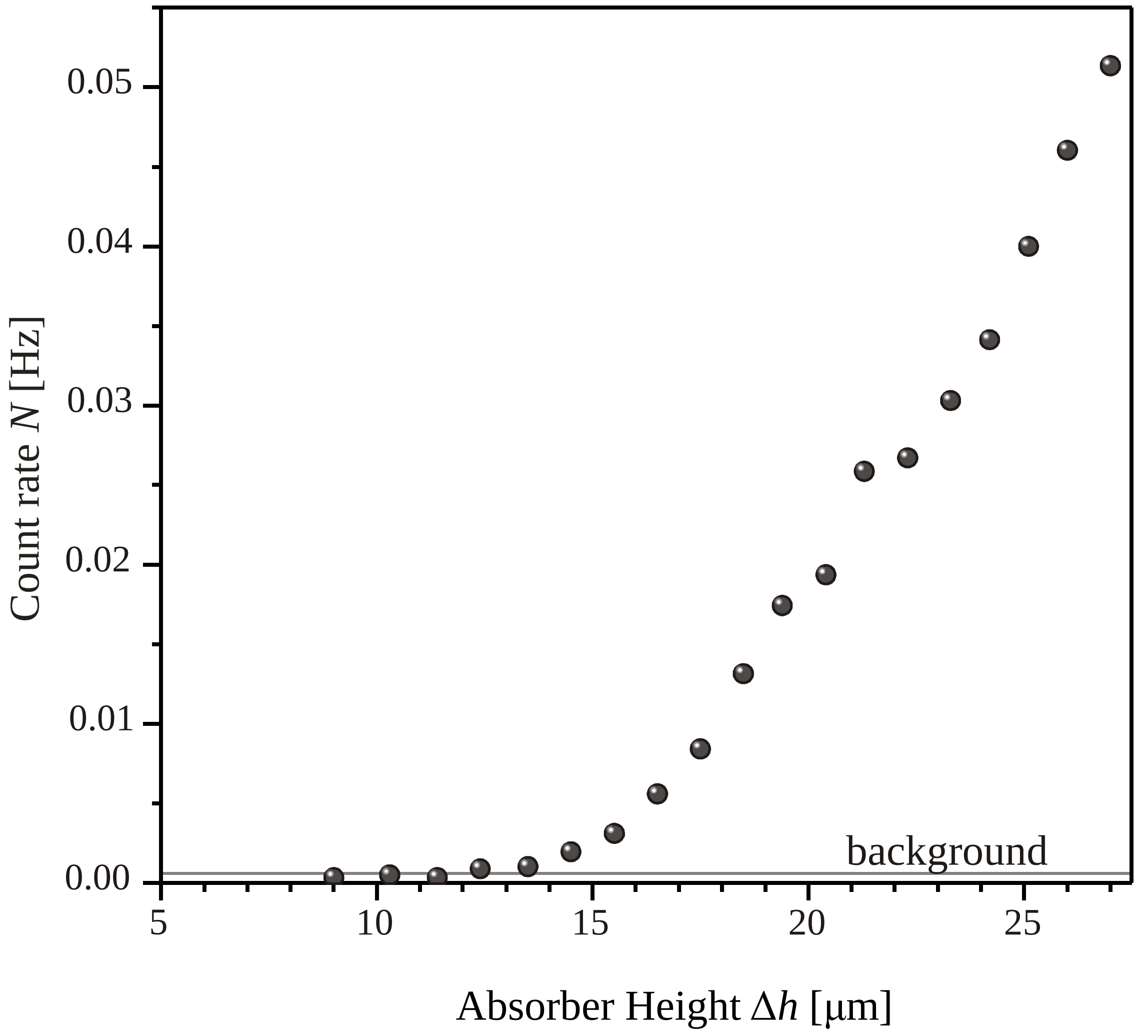
Reached: 1-1.6 µm

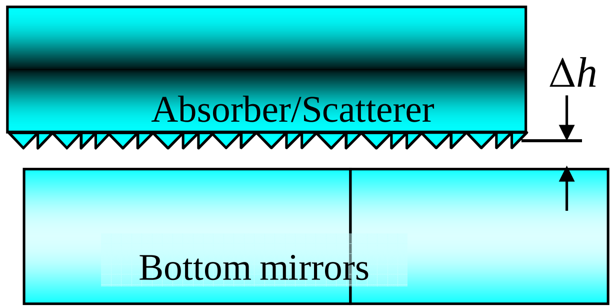
Possible: < 0.5 µm





Detection of the size of the quantum states





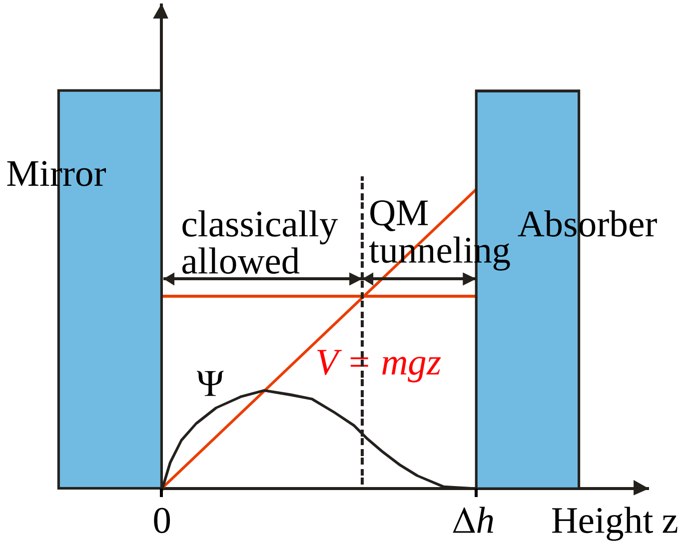
Phenomenological model: The tunneling model

$$\tau_{\text{passage}} = \frac{L}{v_{\text{hor}}}$$

$$T(\Delta h, n) = N_0 \beta_n \exp\left(-\Gamma_n \tau_{\text{passage}}\right)$$

$$\Gamma_n = w_n \cdot P_{n,\text{tunnel}} \cdot \varepsilon_{\text{absorber}}$$

$$P_{n,\text{tunnel}} = \begin{cases} \exp\left(-\frac{4}{3}\left(\frac{\Delta h - z_n}{l_0}\right)^{3/2}\right) & ;\ \Delta h > z_n \\ 1 & ;\ \text{otherwise} \end{cases}$$

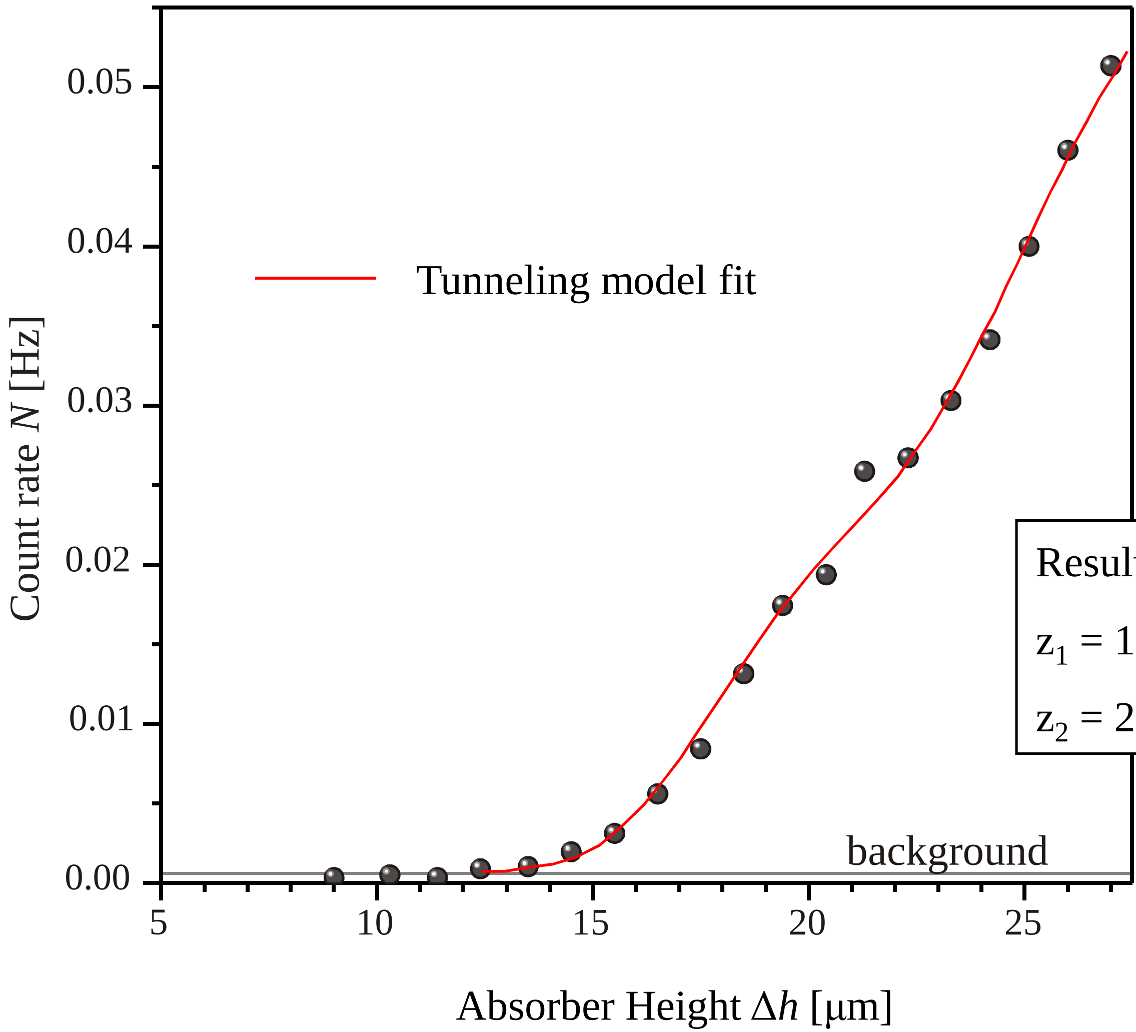


Characteristic length scale:

$$l_0 = \sqrt[3]{\frac{\hbar^2}{2m^2 g}} = 5.87\ \mu\text{m}$$

$$N = \sum_n N_0 \beta_n \exp\begin{cases} -\alpha \frac{L}{v_{\text{horiz}}} \exp\left(-\frac{4}{3}\left(\frac{\Delta h - z_n}{l_0}\right)^{3/2}\right) & ;\ \Delta h > z_n \\ -\alpha \frac{L}{v_{\text{horiz}}} & ;\ \text{otherwise} \end{cases}$$

Detection of the size of the quantum states



Results:

z_1 = 12.2 ± 1.8(syst) ± 0.7(stat) µm

z_2 = 21.6 ± 2.2(syst) ± 0.7(stat) µm

Comparison to theory,

undisturbed wave functions:

z_1 = 13.7 µm

z_2 = 24.0 µm

Why are only the eigenstates discussed?

Neutron flux N after slit:

$$N \propto \int_{v_{hor}} f\left(v_{hor}\right) \int \left| \Psi\left(z, \tau_{\text{passage}} = \frac{L}{v_{hor}} \right) \right|^2 dz \quad \text{with} \quad \psi(z,t) = \sum_n C_n \psi_n(z) e^{\frac{i}{\hbar} E_n \tau_{passage}} e^{-\frac{1}{2\hbar}\Gamma_n \tau_{passage}}$$

Initial occupation numbers: $C_n = \int \psi_{\text{in}}\left(z, \tau_{\text{passage}} = 0\right) \psi_n(z)\, dz$

$$N \propto \int_{v_{hor}} f\left(v_{hor}\right) \sum_{n,k} C_n^* C_k \left\langle \psi_n \middle| \psi_k \right\rangle e^{\frac{i}{\hbar}(E_n - E_k)\tau_{passage}} e^{-\frac{1}{2\hbar}(\Gamma_n + \Gamma_k)\tau_{passage}}$$

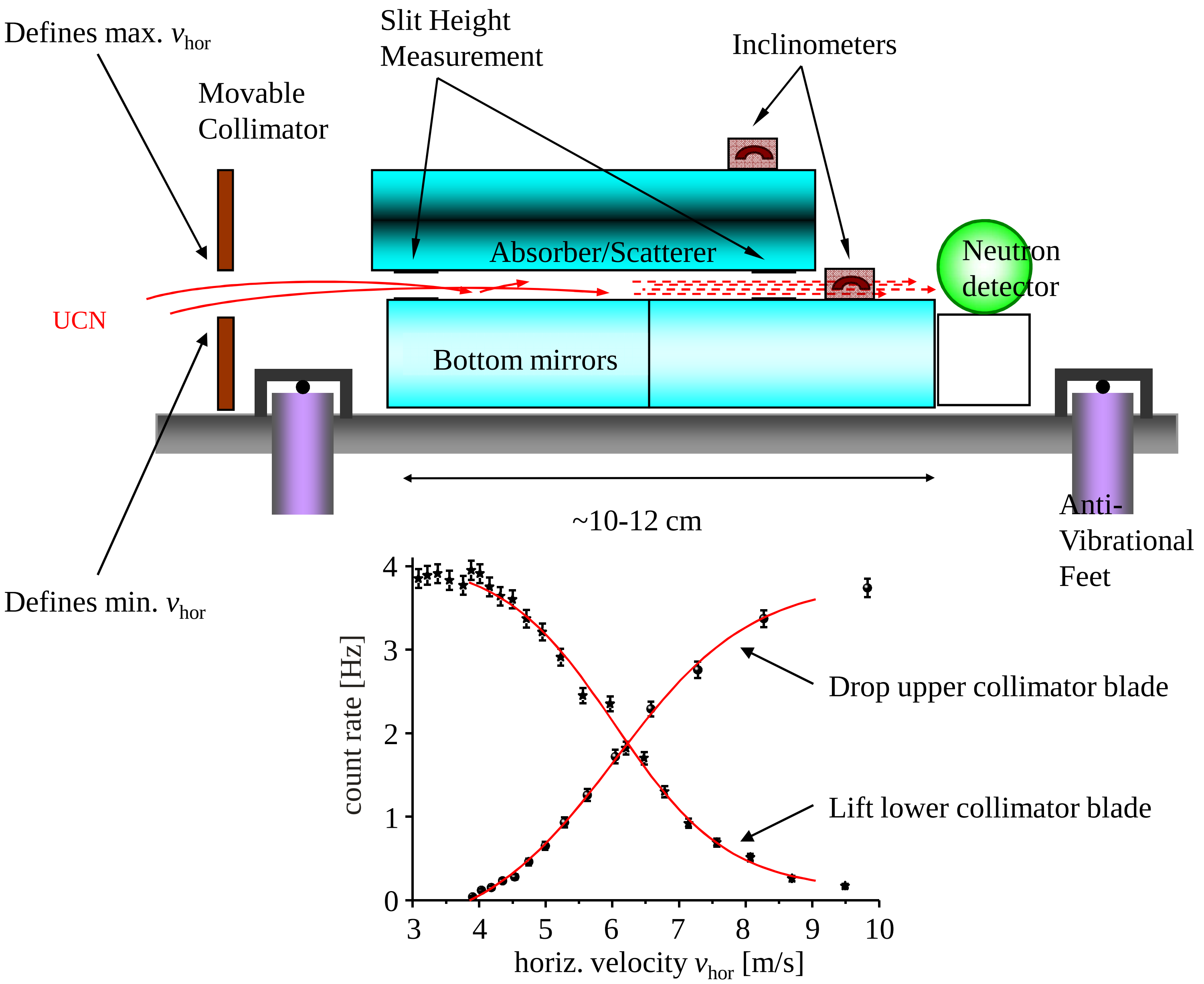
Doesn't vanish for $n \neq k$!

(Non-unitary Hamiltonian)

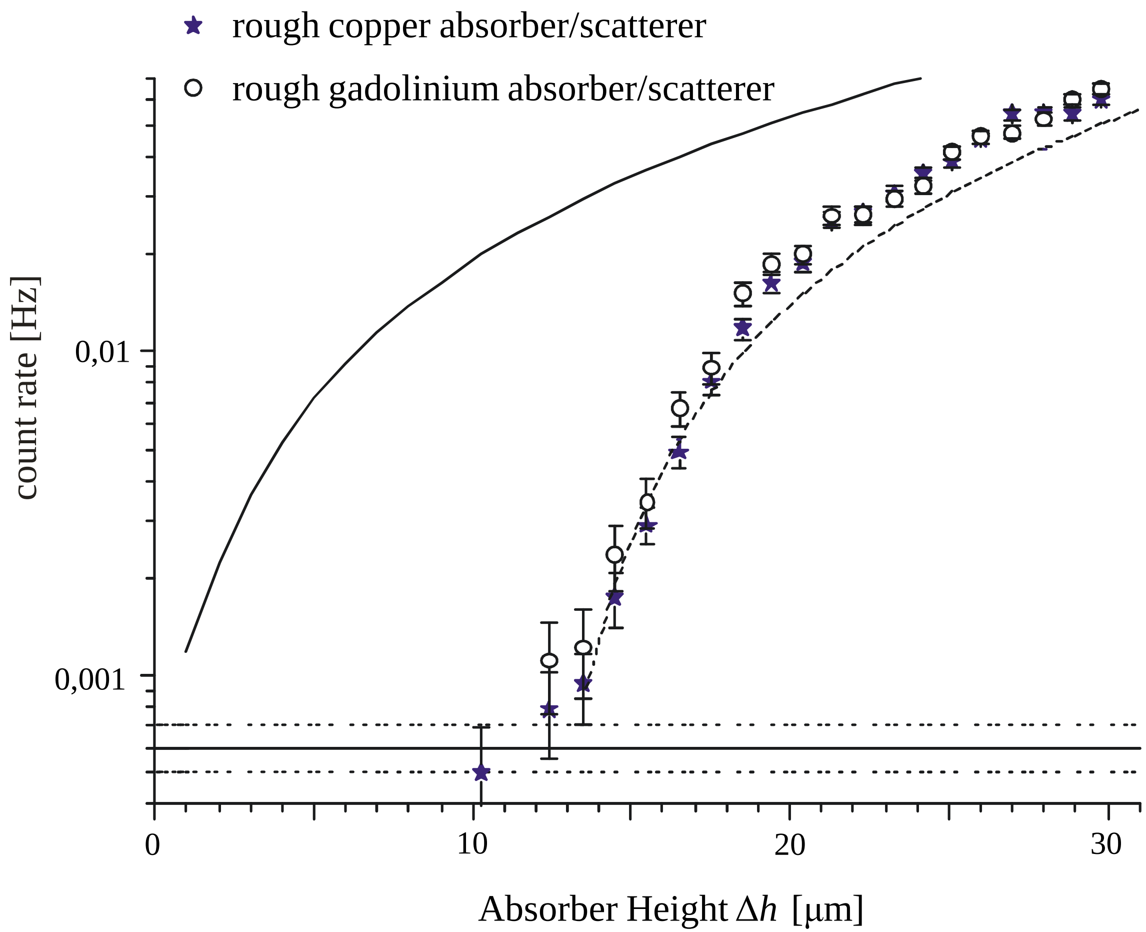
$$= \int_{v_{hor}} f\left(v_{hor}\right) \sum_n \left|C_n\right|^2 e^{-\frac{1}{\hbar}\Gamma_n \tau_{passage}} + \int_{v_{hor}} f\left(v_{hor}\right) \sum_{n \neq k} C_n^* C_k \left\langle \psi_n \middle| \psi_k \right\rangle e^{\frac{i}{\hbar}(E_n - E_k)\tau_{passage}} e^{-\frac{1}{\hbar}\frac{\Gamma_n + \Gamma_k}{2}\tau_{passage}}$$

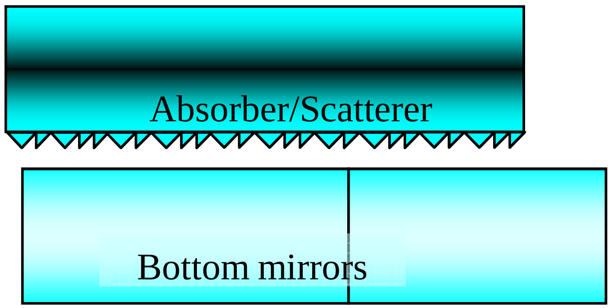
This term is small for polychromatic neutron beam

The horizontal velocity spectrum



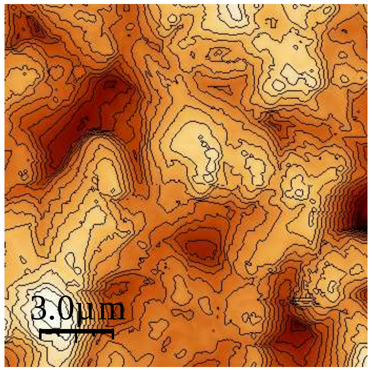
How does an absorber work?





Roughness (2002):

- Standard Deviation: 0,7 µm
- Correlation length: ~ 5 µm



Lesson: It's the roughness which absorbs neutrons. A high imaginary part of the potential doesn't, since the neutron cannot enter.
(see A. Yu. Voronin et al., PRD 73, 44029 (2006))

Cf. Optics: $$R_\perp = \left| \frac{1-n}{1+n} \right|$$

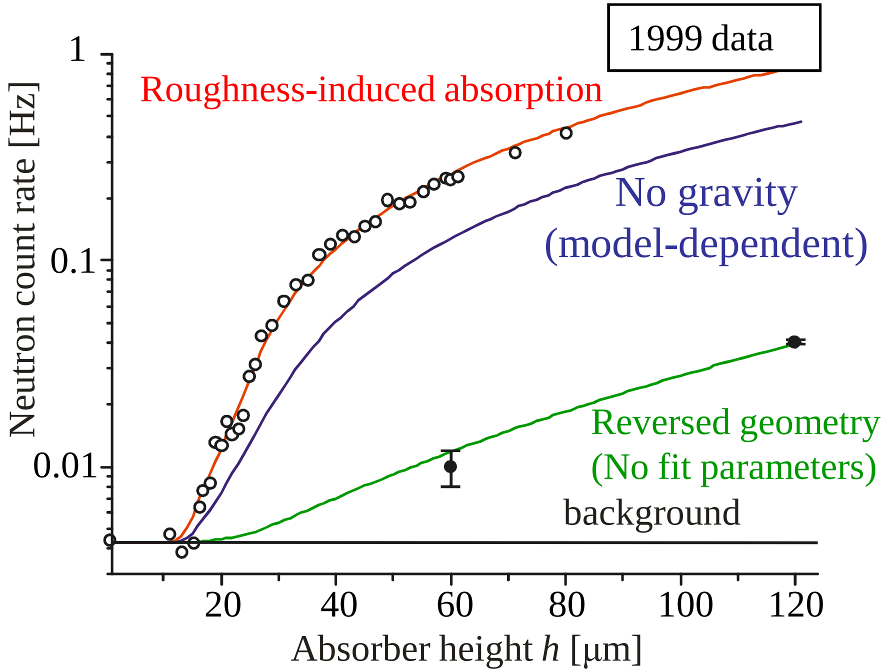
Theoretical description:

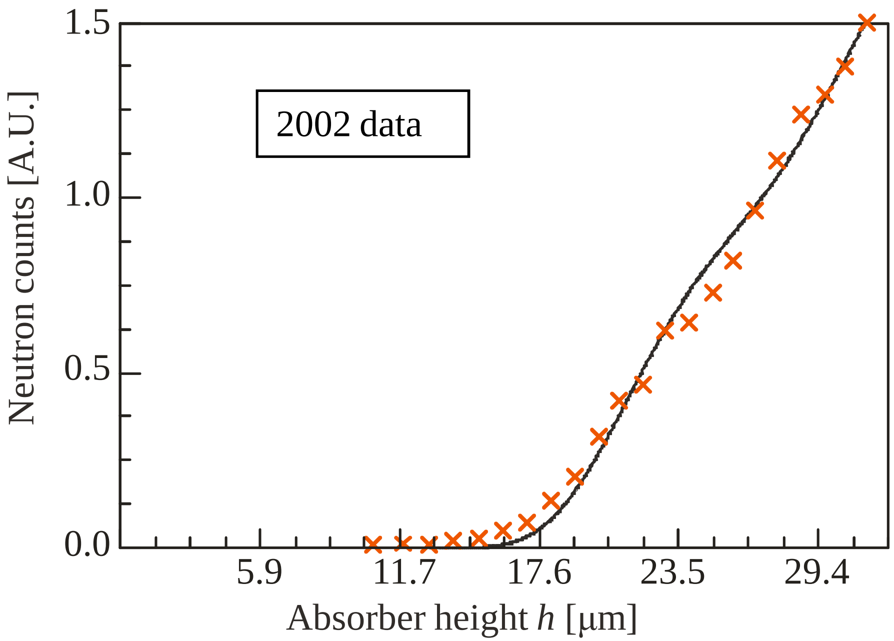
- Tunneling model

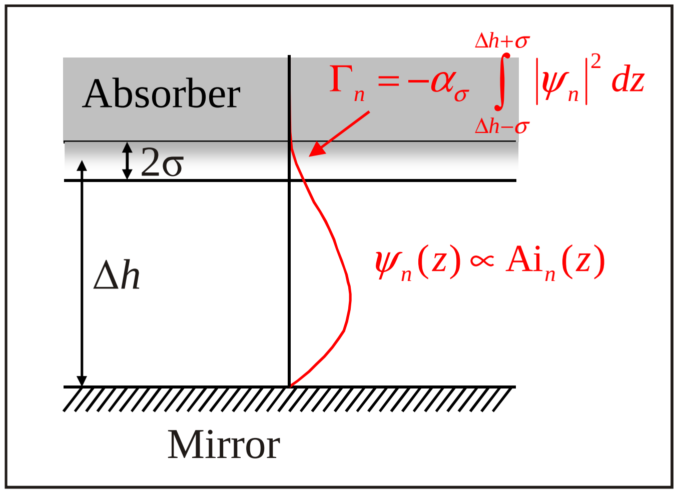
  V. Nesvizhevsky, Eur. Phys. J. C40 (2005) 479

- QM, Flat absorber doesn't work:
- Roughness-induced absorption:

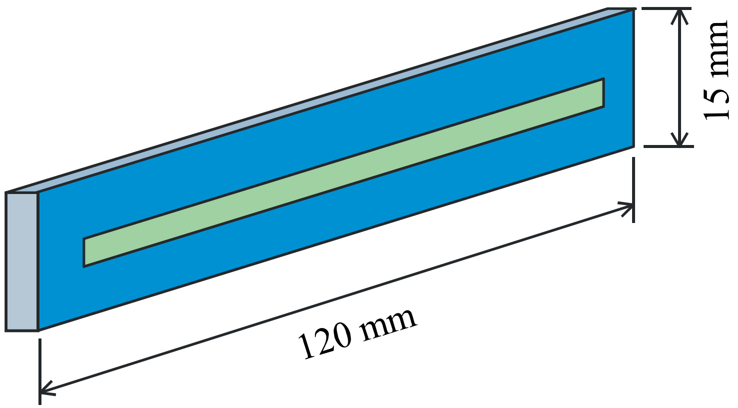
  A.Westphal et al., Eur. Phys. J. C51, 367 (2007)

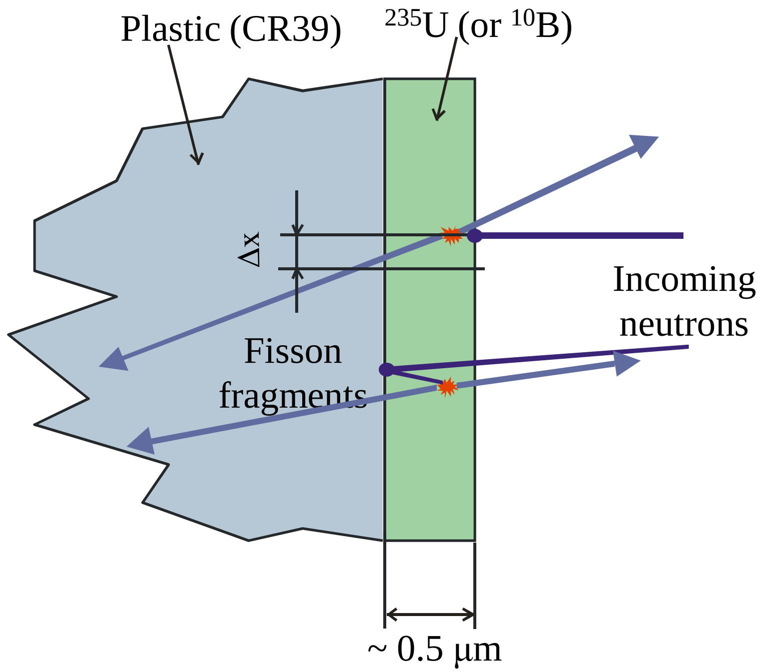


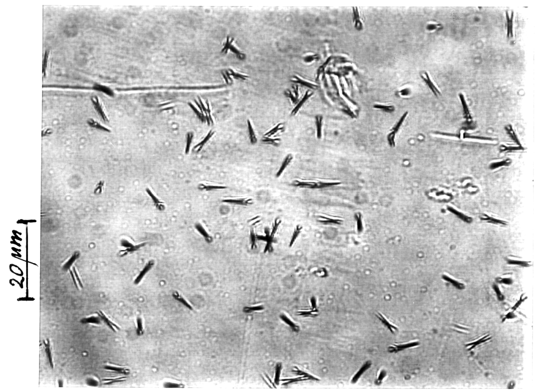




Position-Sensitive Detector

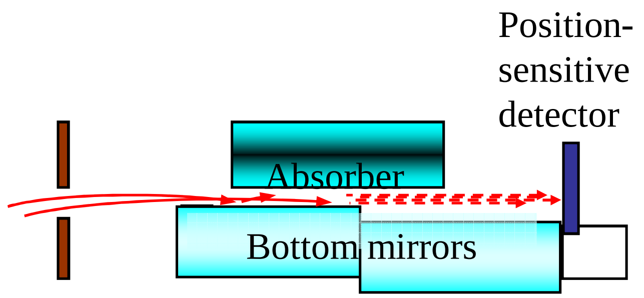


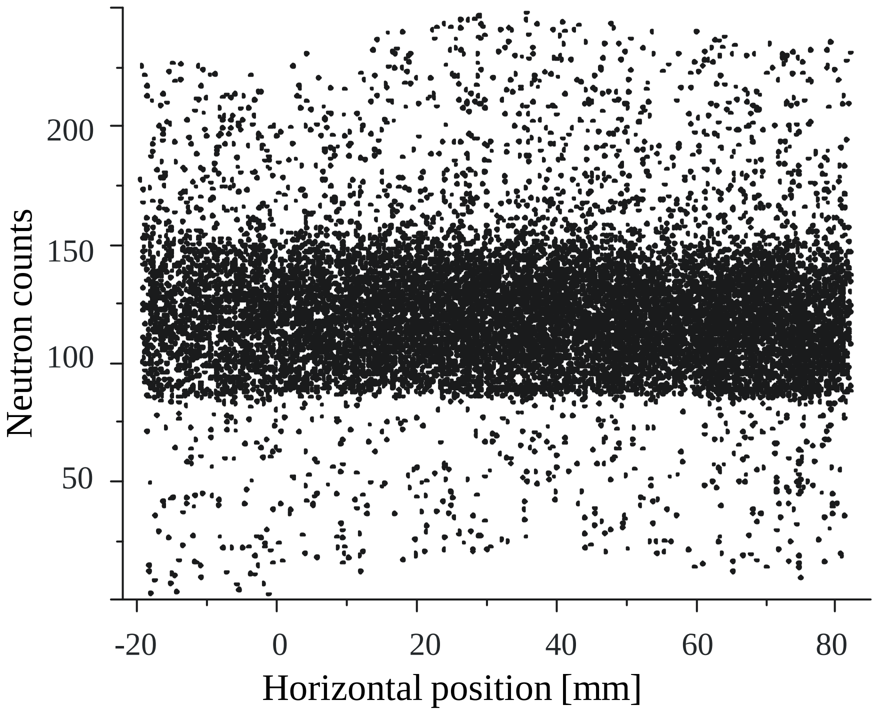




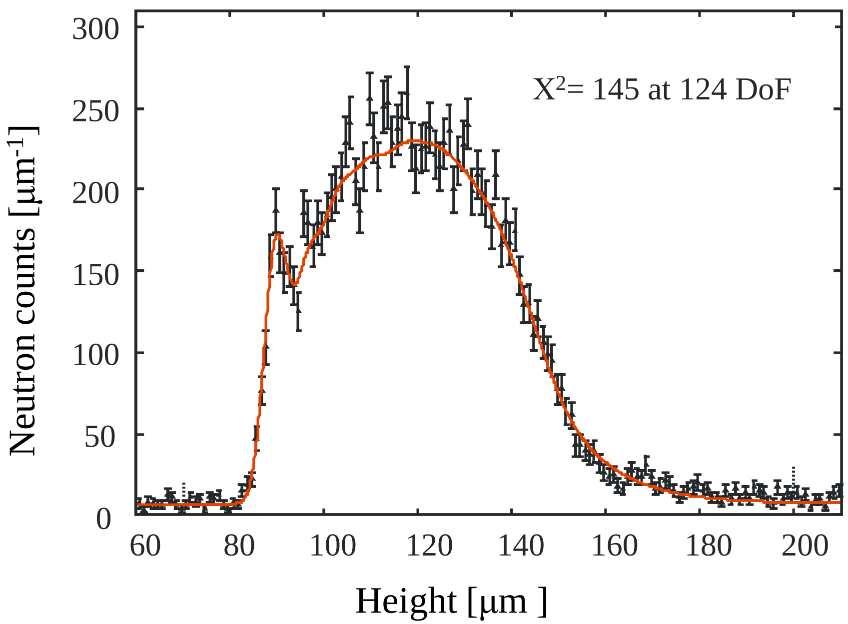
Picture of developed detector with tracks

Results with the Position-Sensitive Detector





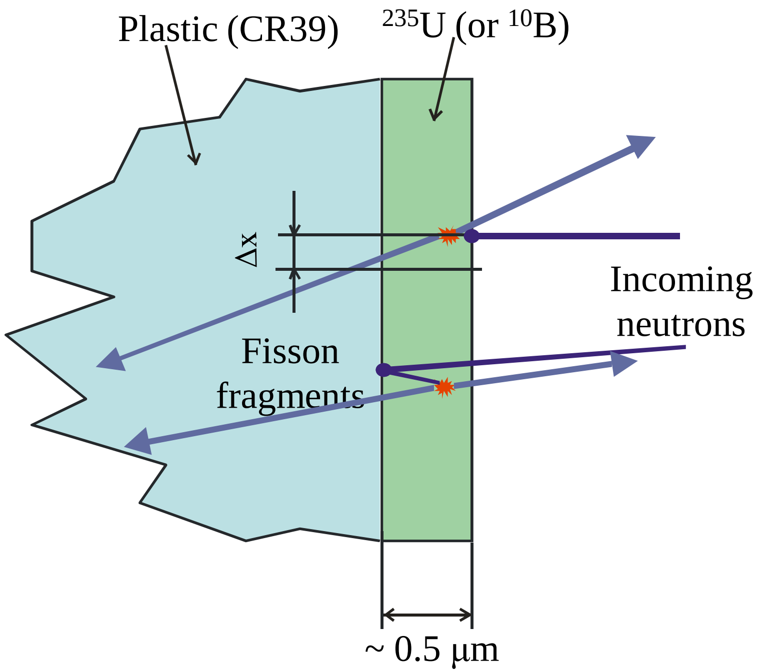
Absorber Height: 50 μm

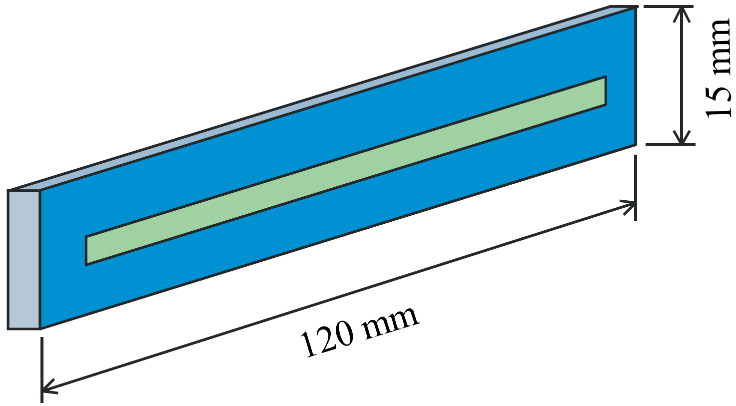


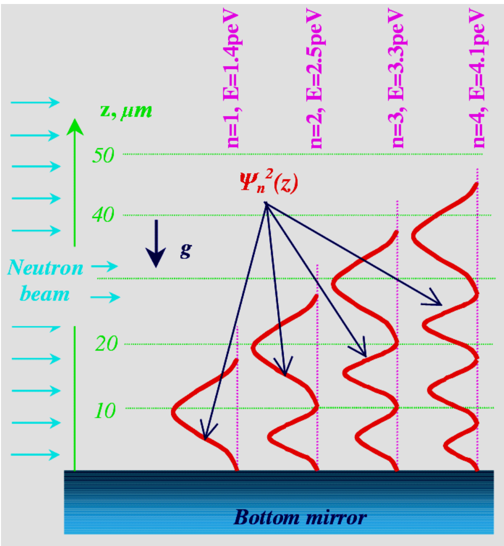
Model from Westphal 2007, ground state suppressed

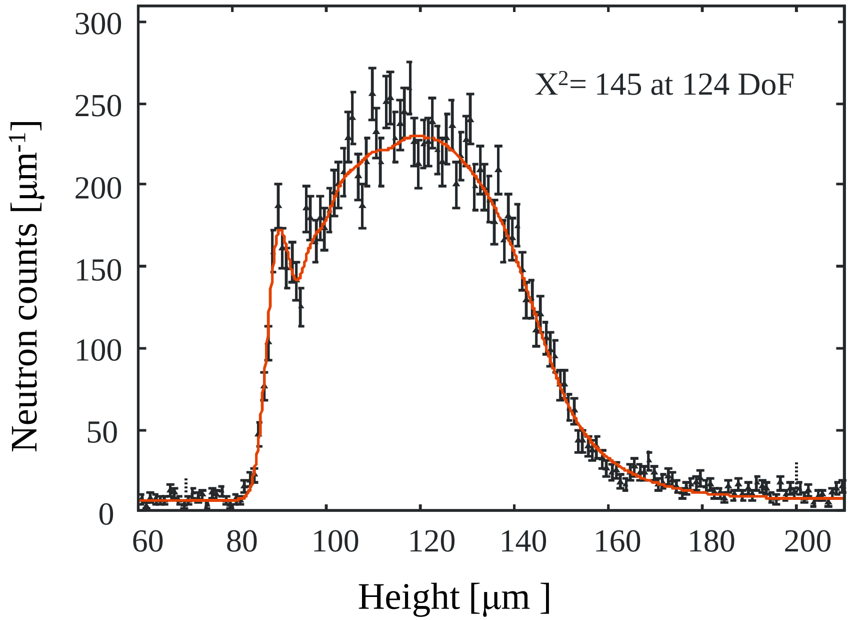
Ch. Krantz, Diploma thesis, Heidelberg (2006)

Results with the Position-Sensitive Detector









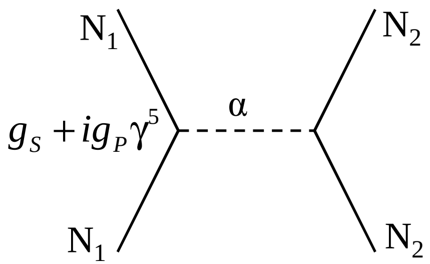
Ch. Krantz, Diploma thesis, Heidelberg (2006)

Application: Search for a new pseudoscalar boson (Axion-like Particle)

Original Proposal for Axion (F. Wilczek, 1978): Solution to the "Strong CP Problem":

Modern Interest: Dark Matter candidate.

All couplings to matter are weak.



Signature of a new pseudoscalar boson: New Short-Range Potential

Monopole-monopole: $V(r) = -g_S^{\,1} g_S^{\,2} \dfrac{(\hbar c)}{4\pi r} \exp(-r/\lambda) \quad \text{with } \lambda = \dfrac{\hbar c}{m_\alpha c^2}$

Looks like 5th force, which is motivated now by theories with extra dimensions. Limits from our experiment exist, but other methods give better limits.

(Westphal et al., hep-ph/0301145, hep-ph/0703108, Nesvizhevsky et al., Class. Quant. Grav. 21, 4557 (2004))

Monopole-dipole: $V(r) = -g_S^{\,1} g_P^{\,2} \dfrac{(\hbar c)^2}{8\pi m_2 c^2} (\sigma_2 \cdot \hat{r}) \left[\dfrac{1}{r\lambda} + \dfrac{1}{r^2}\right] \exp(-r/\lambda)$

Most often done with electrons as polarized particle. Coupling Constants depend on the species.

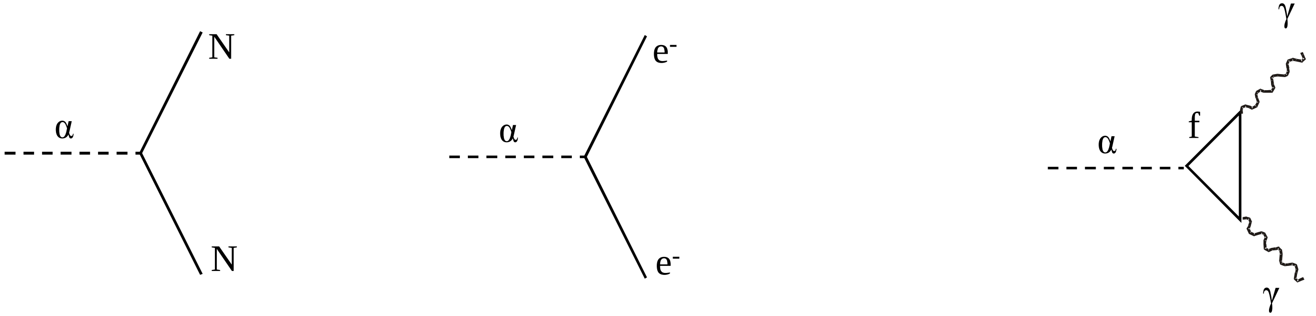
Dipole-dipole: $V(r) \propto g_P^{\,1} g_P^{\,2} \left[(\sigma_1 \cdot \sigma_2) f(r) + (\sigma_1 \cdot \hat{r})(\sigma_2 \cdot \hat{r}) g(r)\right]$

Disappears for an unpolarized source

Application: Search for a new pseudoscalar Boson (Axion-like Particle)

Original Proposal (F. Wilczek, 1978): Solution to the “Strong CP Problem”:

Modern Interest: Dark Matter candidate. All couplings to matter are weak. Maybe to weak for us.



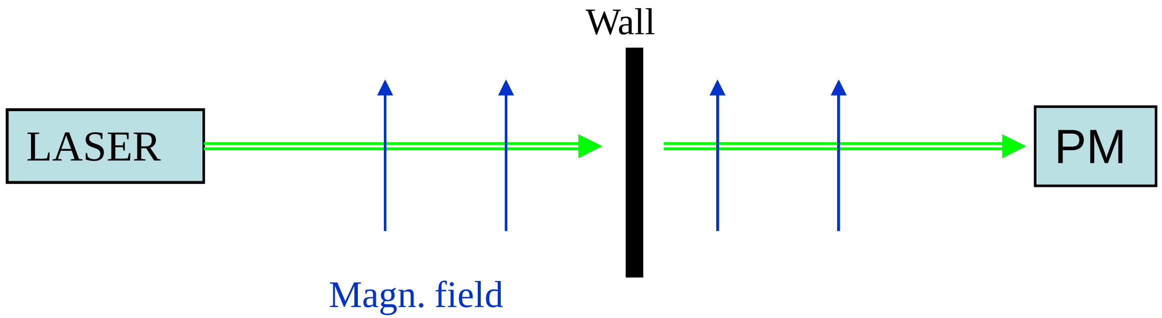
Experimental Signatures:

• Astrophysics und Cosmology

• Particle accelerators (additional decay modes)

• Conversion of Galactic Axions in a magnet field into microwave photons:

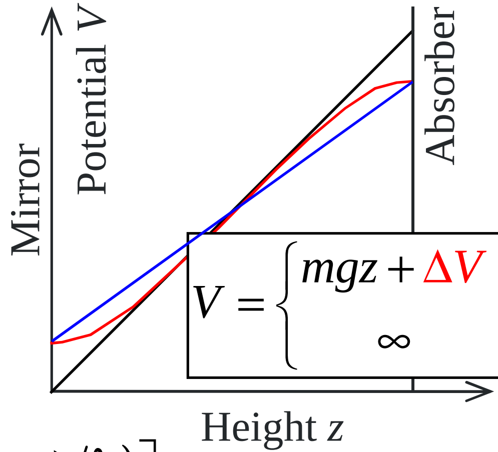
• Light shining through walls:



Effect on Gravitationally Bound States

Integration of 2nd potential over mirror:

$$\Delta V_{\mathrm{mirror}}(z) = -g_S{}^N g_P{}^n \frac{(\hbar c)^2 \rho_{\mathrm{m}} \lambda}{8 m_{\mathrm{n}}{}^2 c^2} \exp(-z/\lambda) \underbrace{(\sigma_n \cdot \hat{z})}_{\pm 1}$$



$$V = \begin{cases} mgz + \Delta V & ; z > 0 \\ \infty & ; \text{otherwise} \end{cases}$$

Inclusion of absorber:

$$\Delta V_{\mathrm{slit}}(z) = \pm g_S{}^N g_P{}^n \frac{(\hbar c)^2 \rho_{\mathrm{m}} \lambda}{8 m_{\mathrm{n}}{}^2 c^2} \underbrace{\left[\exp(-z/\lambda) - \exp(-(\Delta h - z)/\lambda)\right]}_{\frac{2z}{\lambda} + \mathrm{const.}}$$

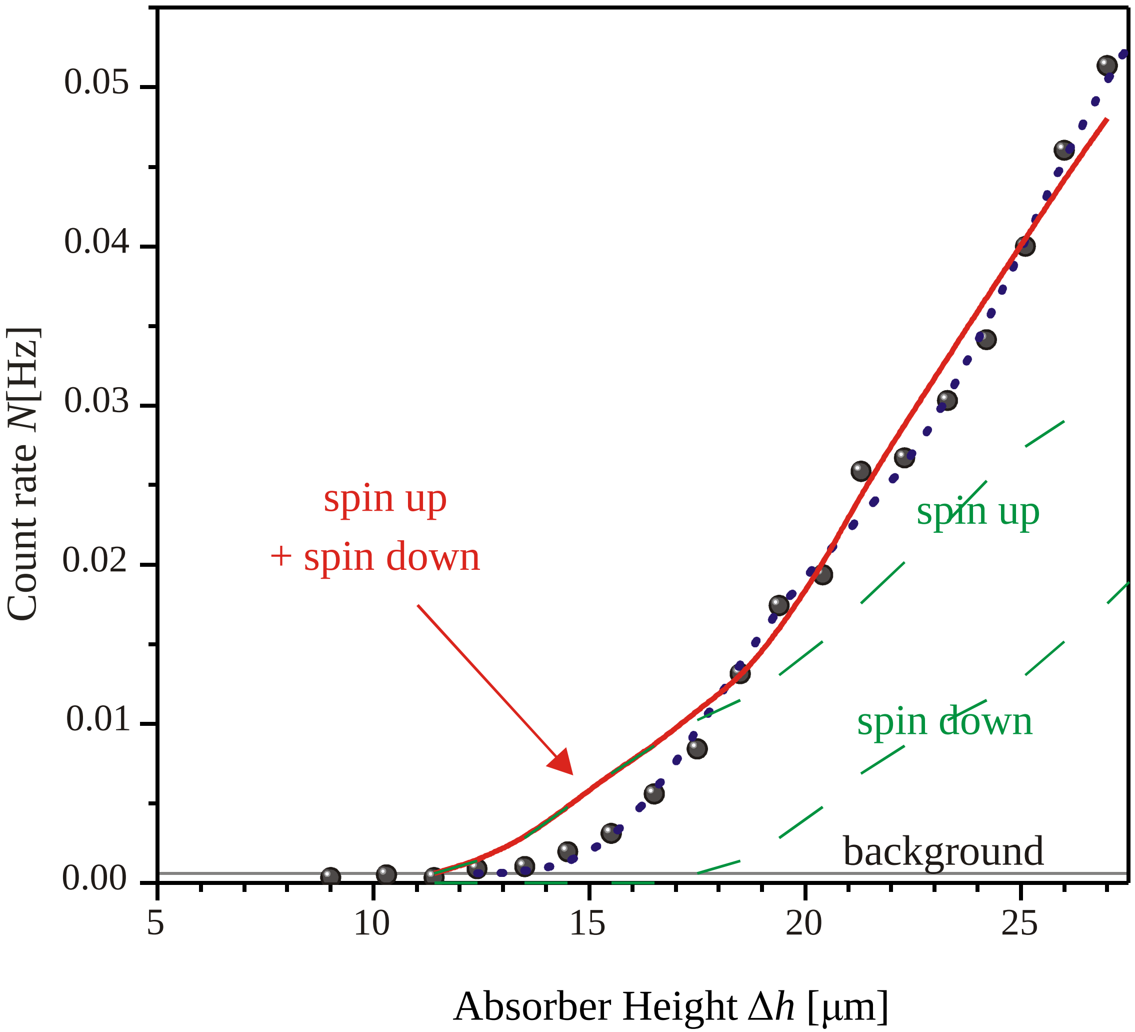
After dropping the invisible constant piece, $V_{\mathrm{slit}}(z)$ is linear in z

$$g \rightarrow g_{\mathrm{eff}} = g \pm g_S{}^N g_P{}^n \frac{2(\hbar c)^2 \rho_{\mathrm{m}}}{8 m_{\mathrm{n}}{}^3 c^2}$$

$$\boxed{\begin{aligned} z_1 &= 2.34 \sqrt[3]{\frac{\hbar^2}{2m^2 g}} = 13.7\ \mu\mathrm{m} \\ z_2 &= 4.09 \sqrt[3]{\frac{\hbar^2}{2m^2 g}} = 24.0\ \mu\mathrm{m} \end{aligned}}$$

Extraction of our Limit

Why can we use unpolarized neutrons?



Limits are calculated from a shift of the turning point by 3 µm.

(PRD 75, 075006 (2007),

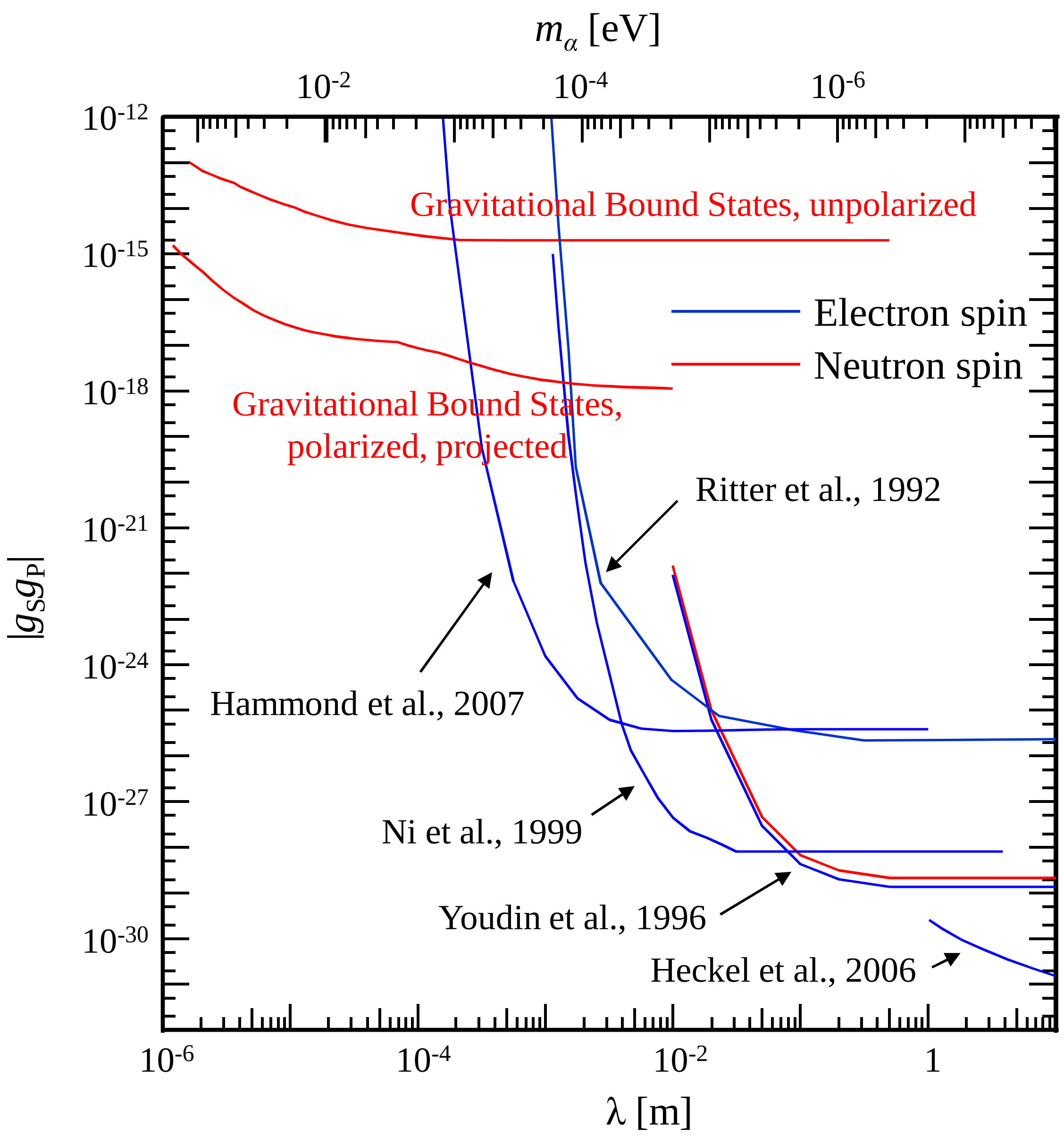
hep-ph/0610339,

hep-ph/0703108))

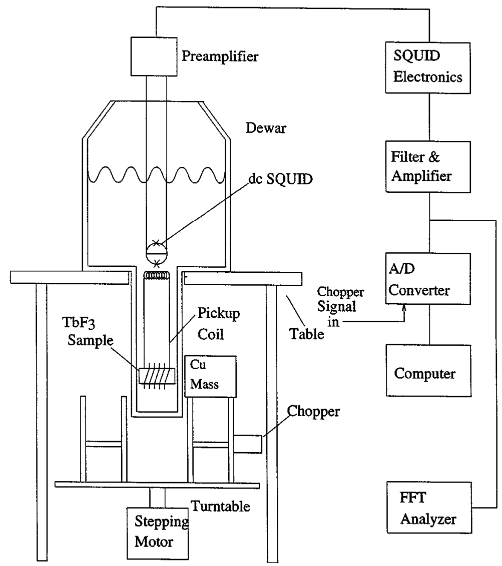
Sensitivity only to magnetic field gradients:

Signal > 1 mT/cm

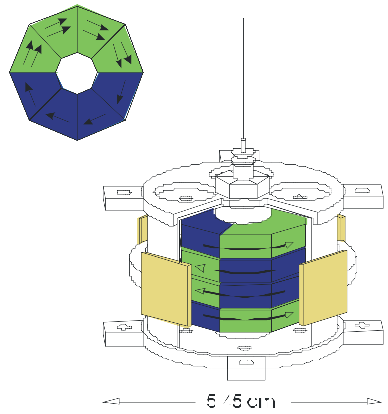
Exclusion Plot for new spin-dependent forces



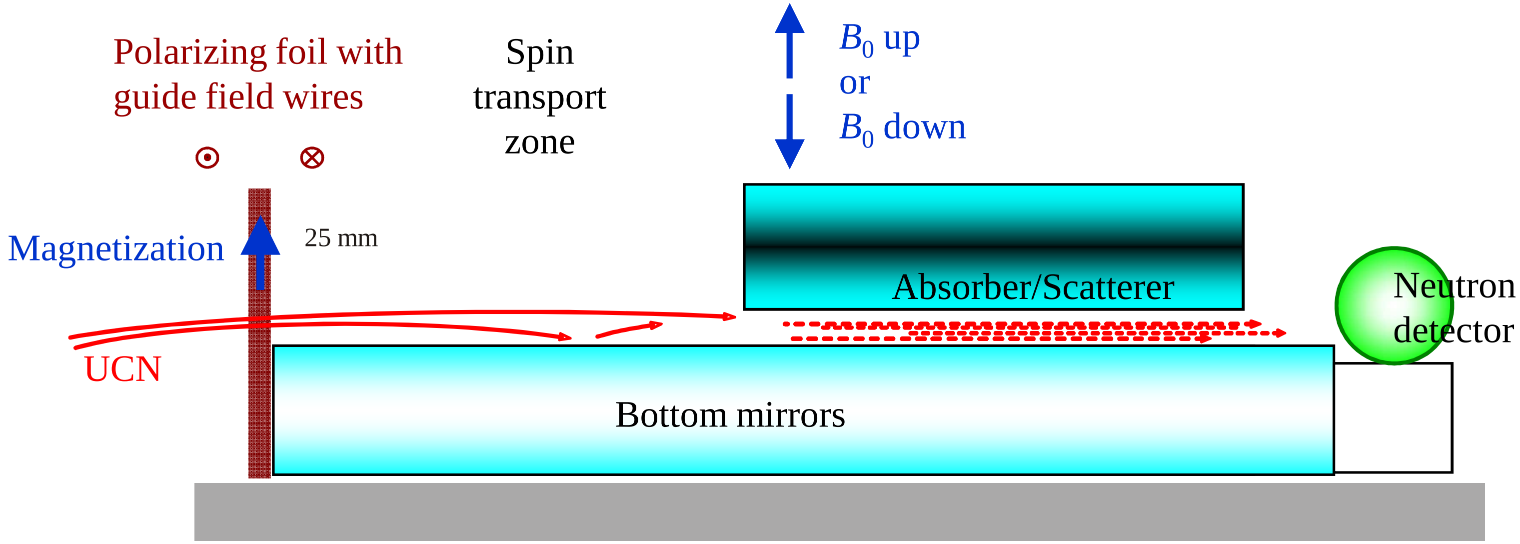
Ni et al., 1999:

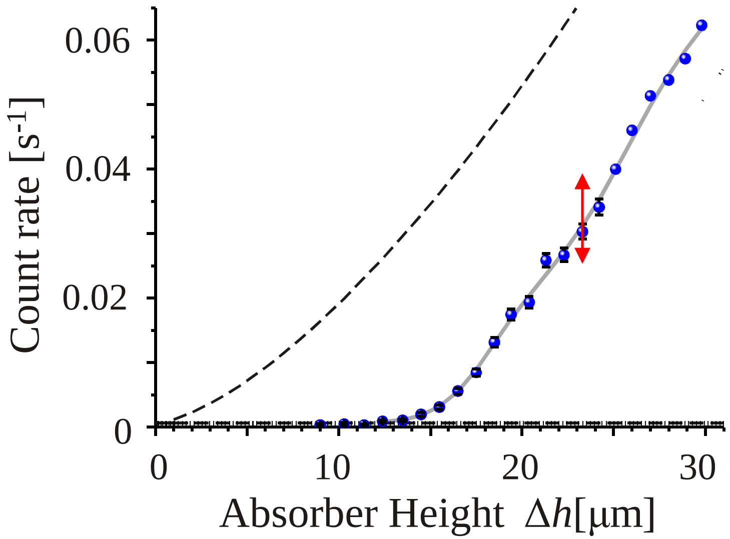


Heckel et al., 2006:



Projected improvement: Polarized experiment





Sensitivity gain due to relative measurement, stronger UCN source, wider mirror, longer run time.

Possible false effect due to magnetic field gradient > 1 μT/cm from holding field or ferromagnetic particles in mirror

Test: Reverse magnetic field, check absorber height dependence, magnetize mirror in strong field

Experiment to be performed in Summer 2009

Energy measurements

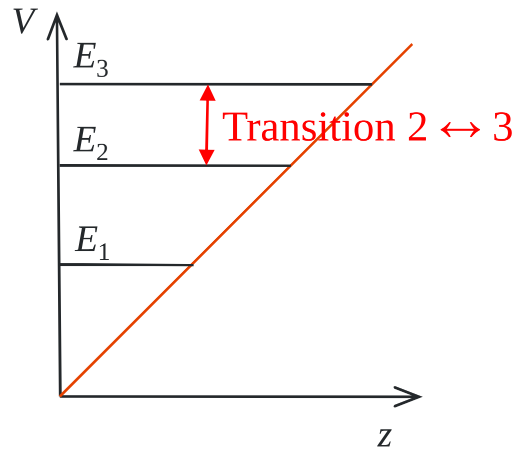
Accuracy of position-Observables: ~ 10%

Improvement: do **spectroscopy**

Idea: Induce state transitions through:

- **Oscillating magnetic field gradients**
- Oscillating Masses
- Vibrations

Typical energy differences: $\Delta E \sim h \cdot 260$ Hz



Additional collaborators:

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A. Meyerovitch, (U Rhodes Island)

Theory of resonance transitions

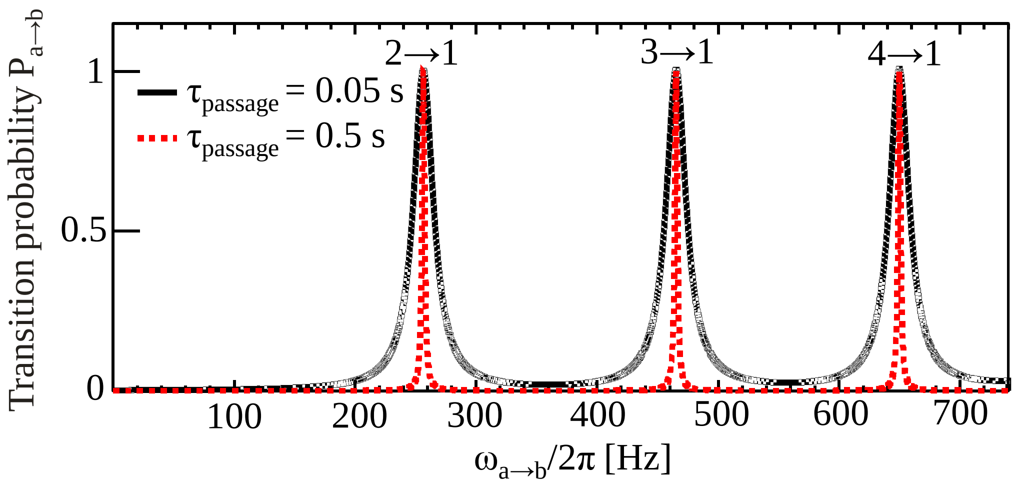
$$H = \underbrace{\frac{\hbar^2}{2m_\mathrm{n}}\frac{\partial}{\partial z} + mgz}_{H_0\text{, defines }\psi_n} + \mathrm{Re}\Big(\underbrace{V(z)}_{\text{i.e.}\,V(z) = -\mu_z \frac{\partial B_z}{\partial z} z}\, \mathrm{e}^{i\omega t}\Big)$$

$$\omega_\mathrm{ab} = E_b - E_a$$

$$\Omega_\mathrm{ab} = \frac{2}{\hbar}\left|\langle b | V(z) | a \rangle\right|$$

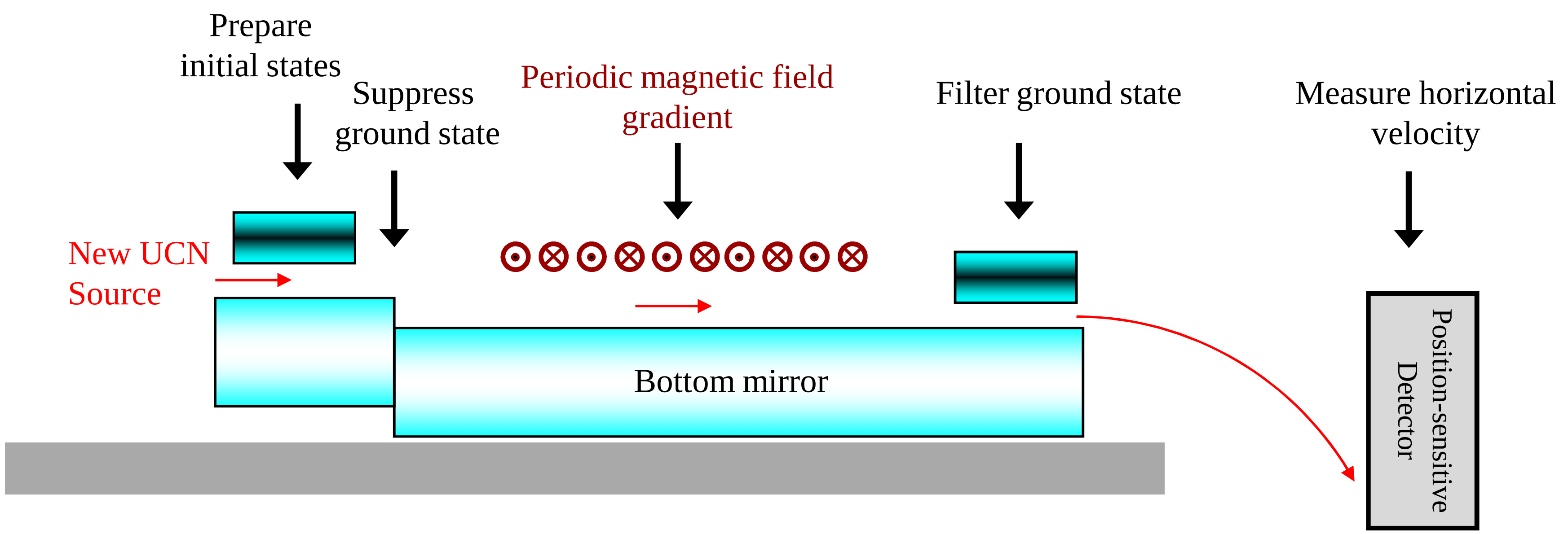
$$\boxed{P_{\mathrm{a}\to\mathrm{b}}\left(\tau_\mathrm{passage}\right) = \Omega_\mathrm{ab}{}^2 \frac{\sin^2\left(\sqrt{\left(\omega - \omega_\mathrm{ab}\right)^2 + \Omega_\mathrm{ab}{}^2}\,\frac{\tau_\mathrm{passage}}{2}\right)}{\left(\omega - \omega_\mathrm{ab}\right)^2 + \Omega_\mathrm{ab}{}^2}}$$

0



G. Pignol et al., 2008

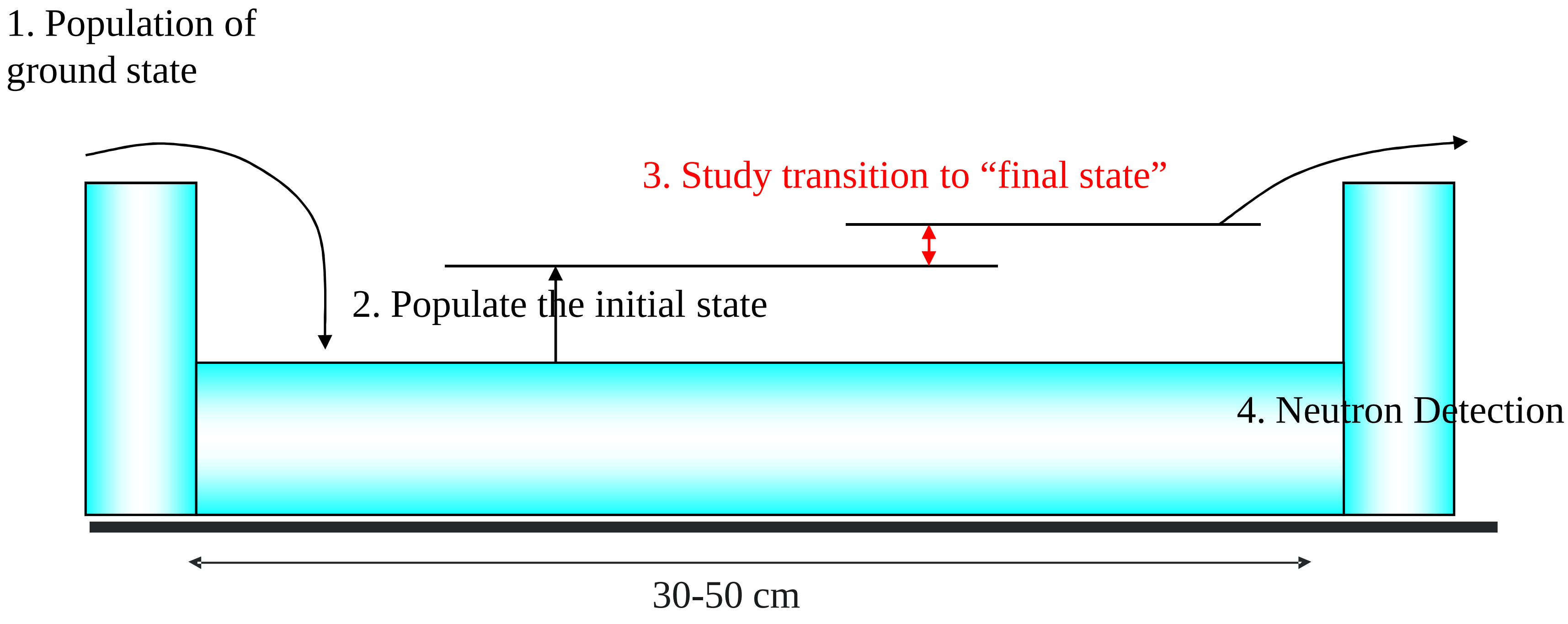
Projected first measurement of resonance transitions



1. Preparation of initial state
2. Suppress ground state
3. Induce Transitions in time-dependent magnetic field gradient
4. Detect ground state in dependence of horizontal velocity (that is: oscillation frequency)

G. Pignol et al., 2008

Under construction: the GRANIT spectrometer



Challenge: Tolerances to get a high neutron lifetime in a given state:

Flatness of bottom mirror: < 100 nm

Accuracy of setting the side walls perpendicular: ~ 10^{-5}

Vibrations, Count Rate, Holes, Vacuum, Dust, …

Summary

- Gravitationally Bound Quantum States detected with Ultracold Neutrons
- Characteristic size is ~ μm
- Applications in fundamental physics: Limits on fifth Forces, limits on spin-dependent forces, and others
- Future: Replace transmission measurements (with its need to rely on absorber models) by energy measurements. Ultimately, $\Delta E/E \sim 10^{-6}$ @ $E \sim peV$ might be reached.

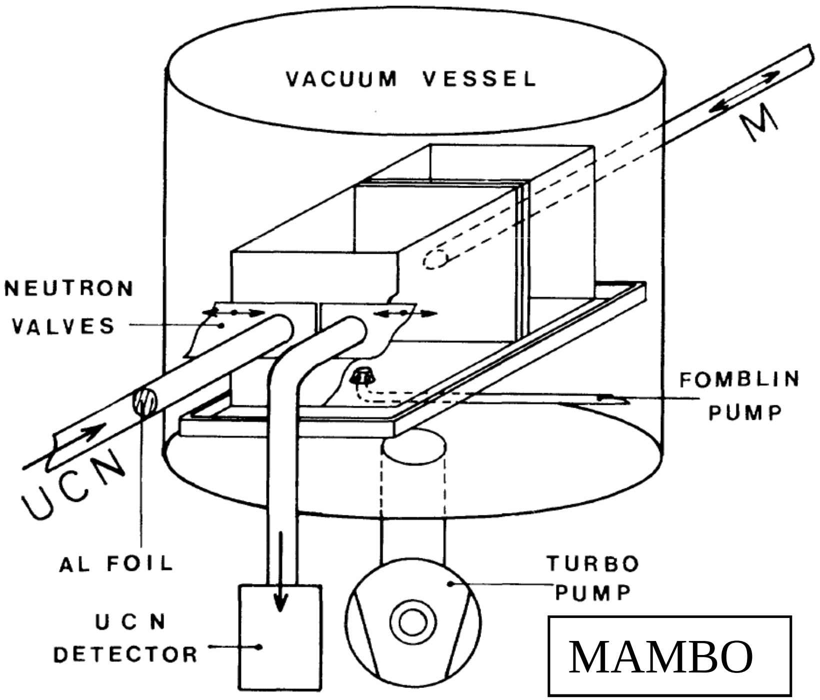
Thank you for your interest!

[redacted]

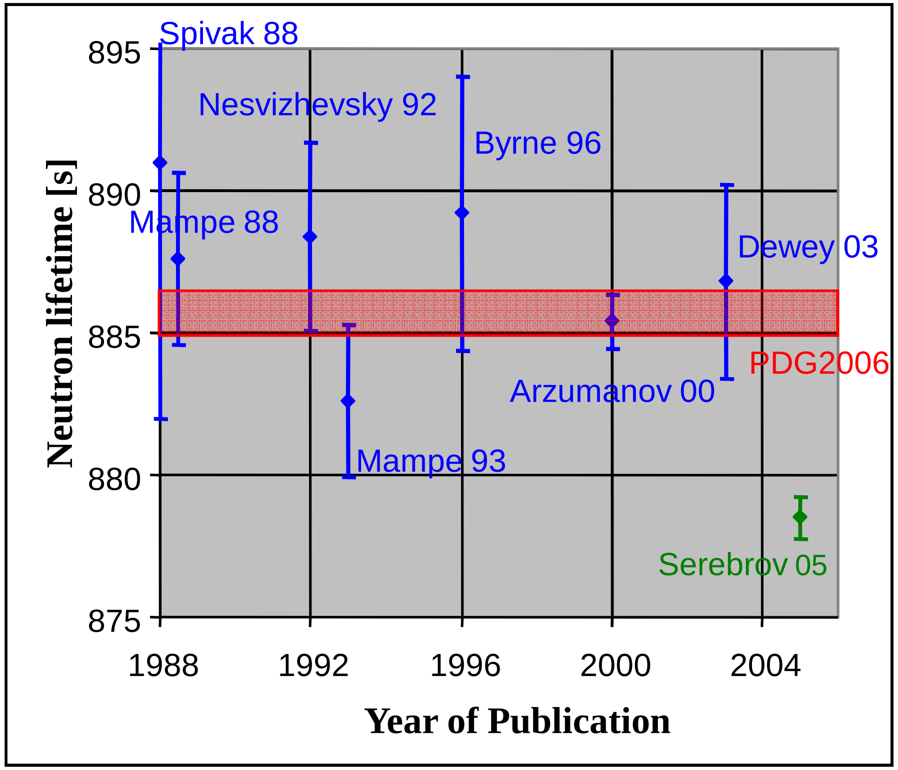
Example: Neutron Lifetime Measurements

Decrease of Neutron Counts N with storage time t: $N(t) = N(0)\exp\{-t/\tau_{eff}\}$

$1/\tau_{eff} = 1/\tau_{\beta} + 1/\tau_{wall\ losses}$

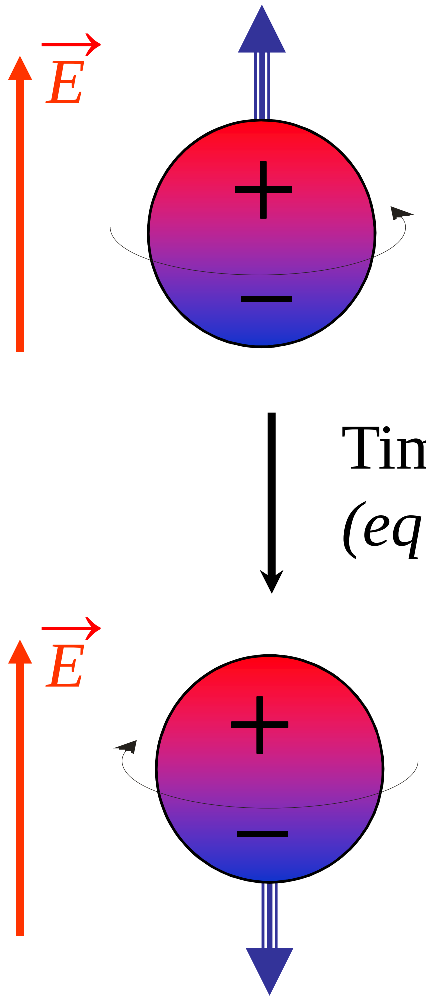


MAMBO



Many new attempts planned, mostly with magnetic bottles

A neutron electric dipole moment (EDM) and *T* violation



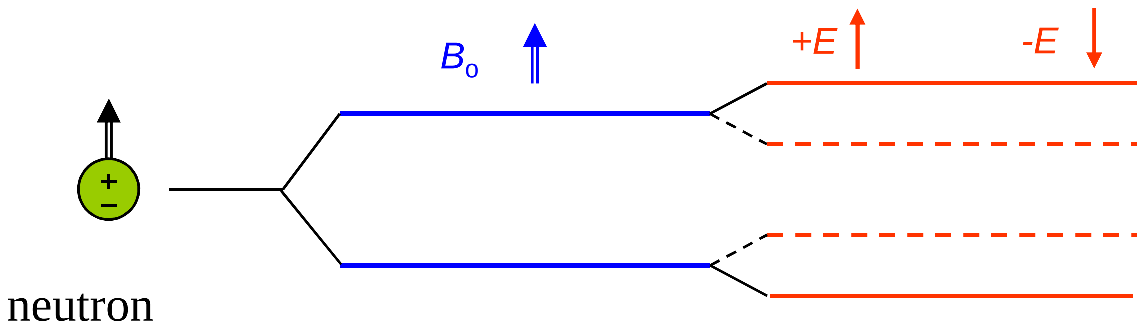
Time Reversal *T*
(equivalent to CP)

If *T* were a good symmetry

and $d_n \neq 0$,

then the ground state of the neutron in a shell modell would be fourfold degenerate

Idea of the EDM measurement



$\omega_n = -B_o\mu/\hbar$

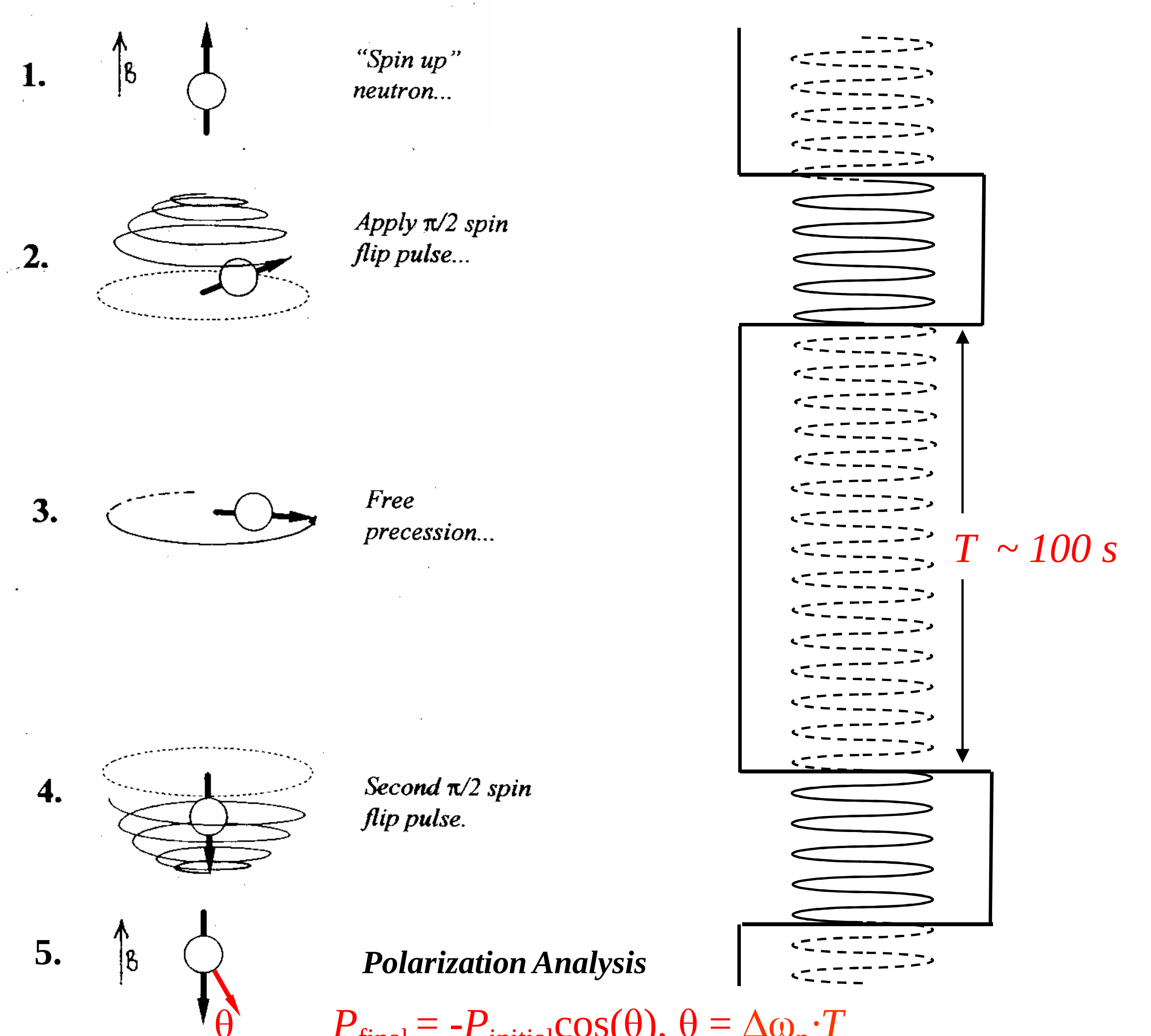
$\omega_n(\uparrow\uparrow) = [-B_0\mu - 2Ed_n] / \hbar$

$\omega_n(\uparrow\downarrow) = [-B_o\mu + 2Ed_n] / \hbar$

The difference in the precession frequency $\Delta\omega_n$ for different electric field directions is proportional to d_n:

$$\Delta\omega_n = (\omega_n(\uparrow\uparrow) - \omega_n(\uparrow\downarrow)) = -4Ed_n/\hbar$$

The Ramsey Method of Separated Oscillatory Fields



$$P_{final} = -P_{initial}\cos(\theta),\ \theta = \Delta\omega_n \cdot T$$

The Ramsey Resonance Curve