Fundamental physics with neutrons

Stefan Baessler

Physics building, rm 169, new wing

University of Virginia
Inst. Nucl. Part. Phys.

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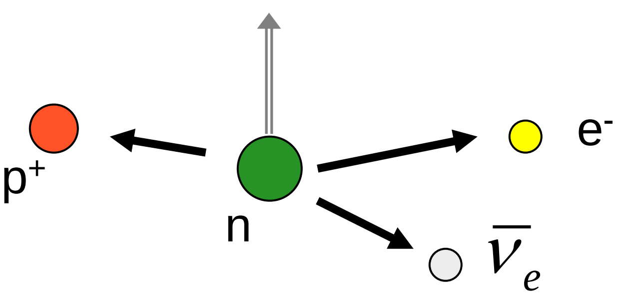
Precision experiments in my lab:

- Neutron beta decay
- Gravitationally bound quantum states of neutrons



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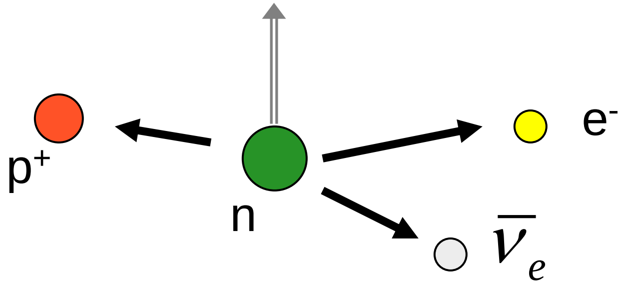

Parity Conservation in Nature

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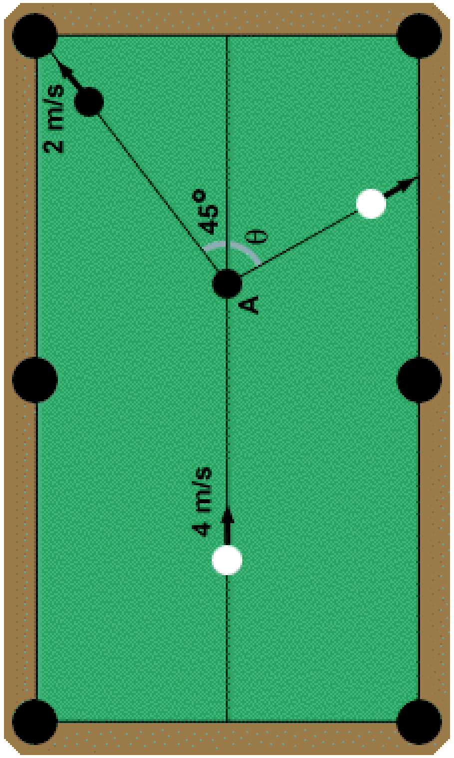

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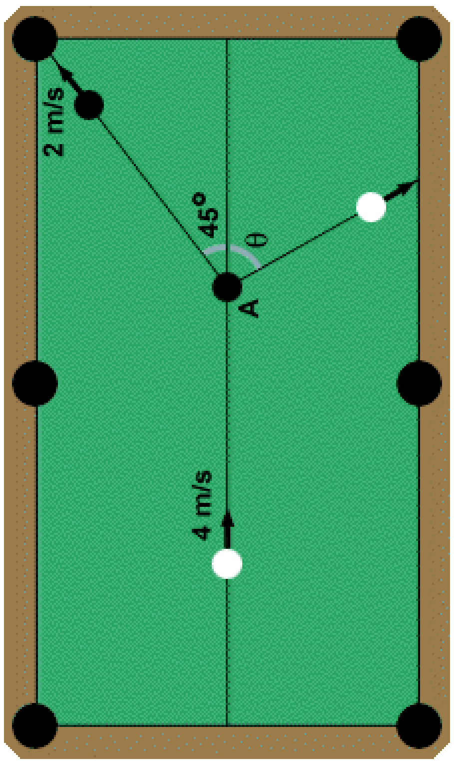

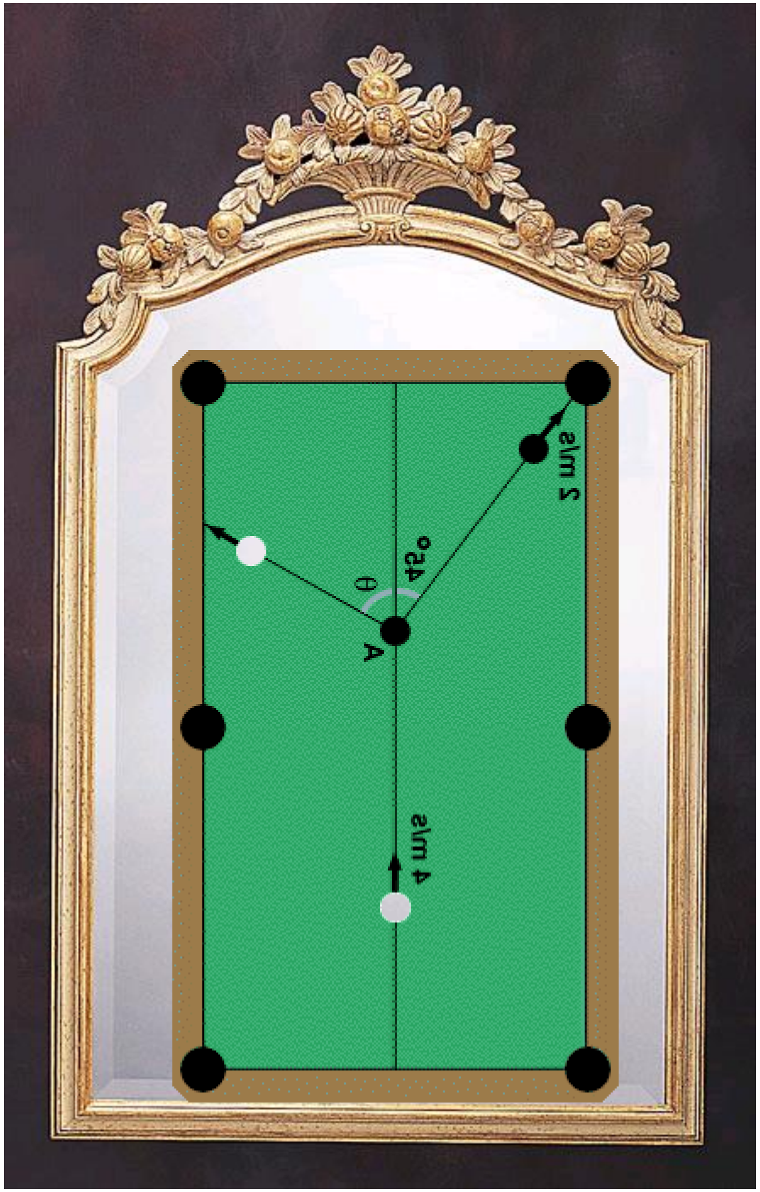

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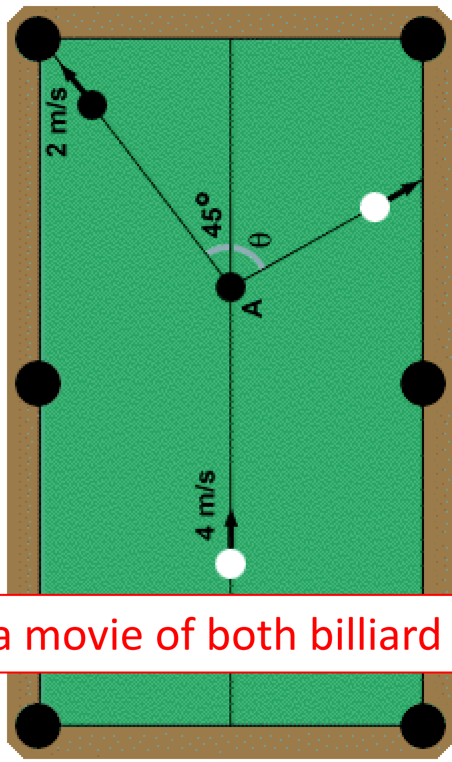

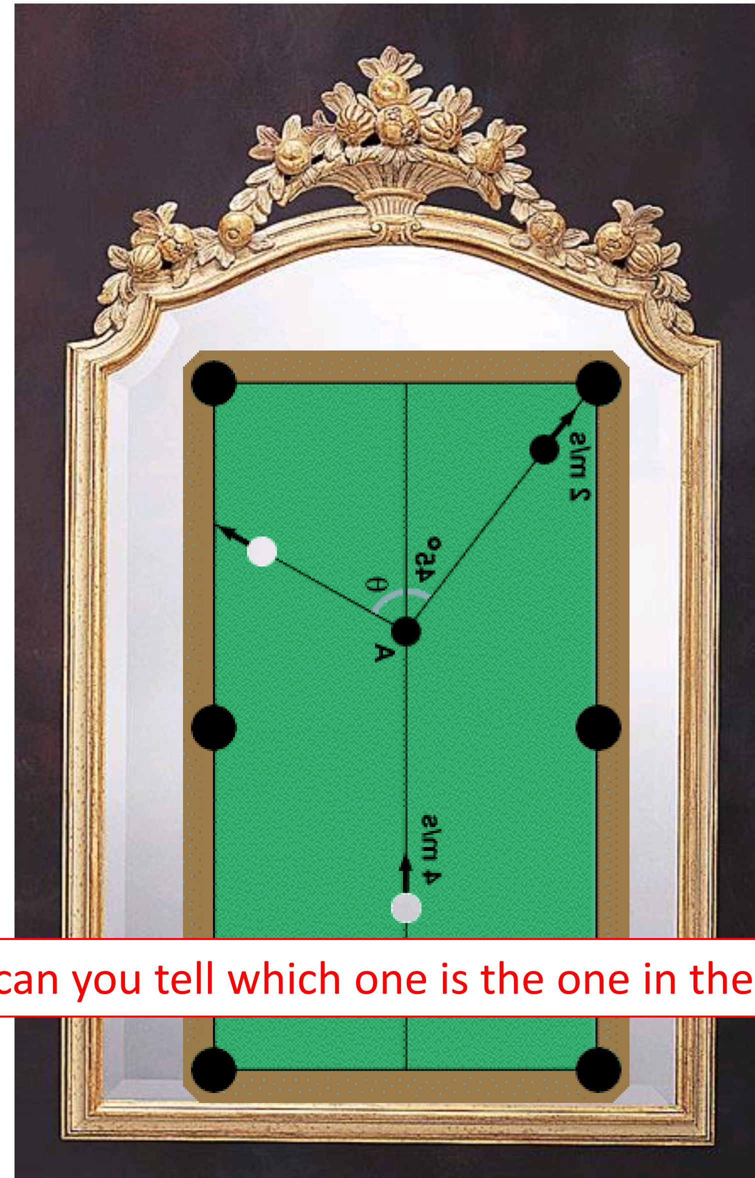

If you get a movie of both billiard tables, can you tell which one is the one in the mirror?

Parity Violation in nature could be by convention

Mechanics:
Parity violation by convention

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Mechanics:
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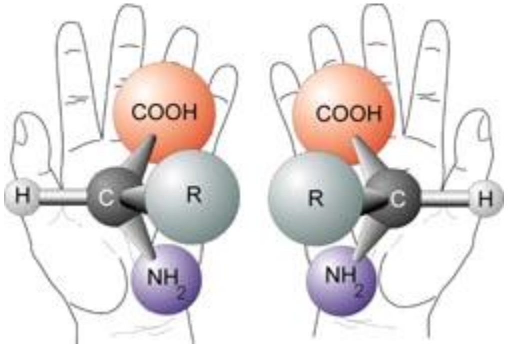
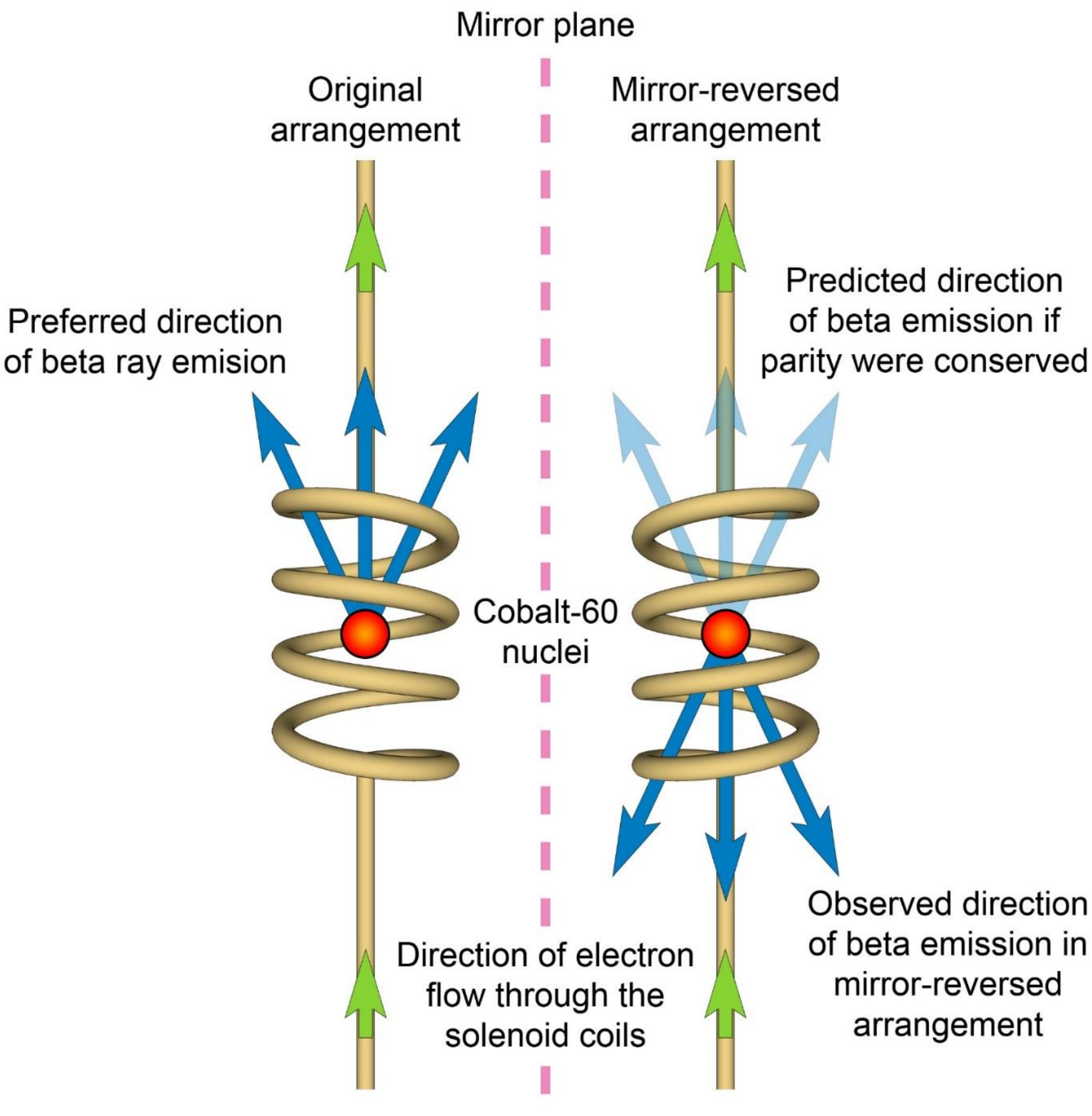
Chemistry / biology:
Parity of in amino acids



Problem: chemical properties of enantiomeres mostly identical, still we have preferred chirality for sugars and amino acids in biological systems. The cause is not known; it could be fundamental or by convention.

Parity Violation in nature in laws of physics



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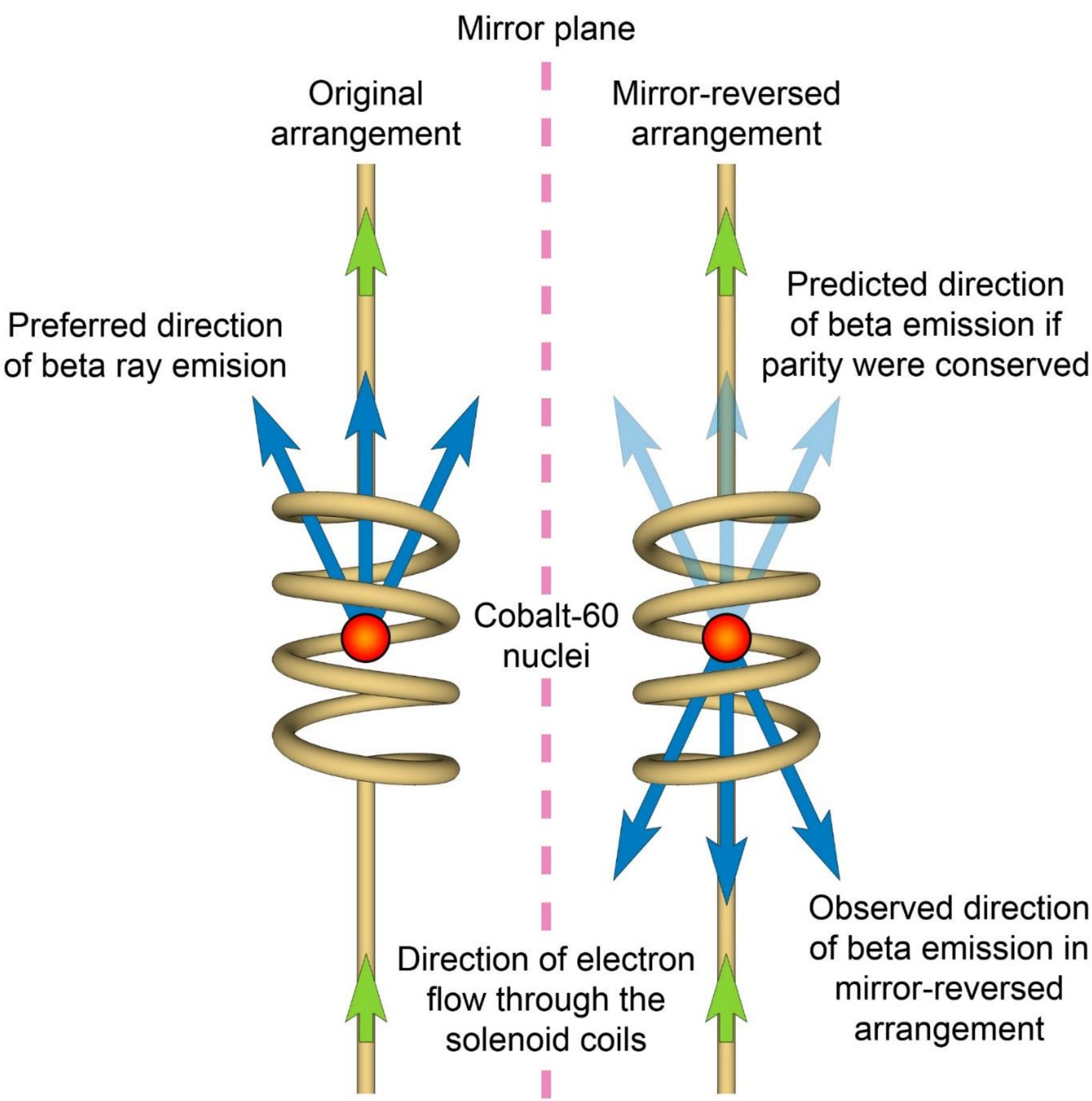
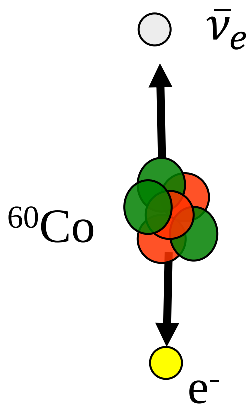


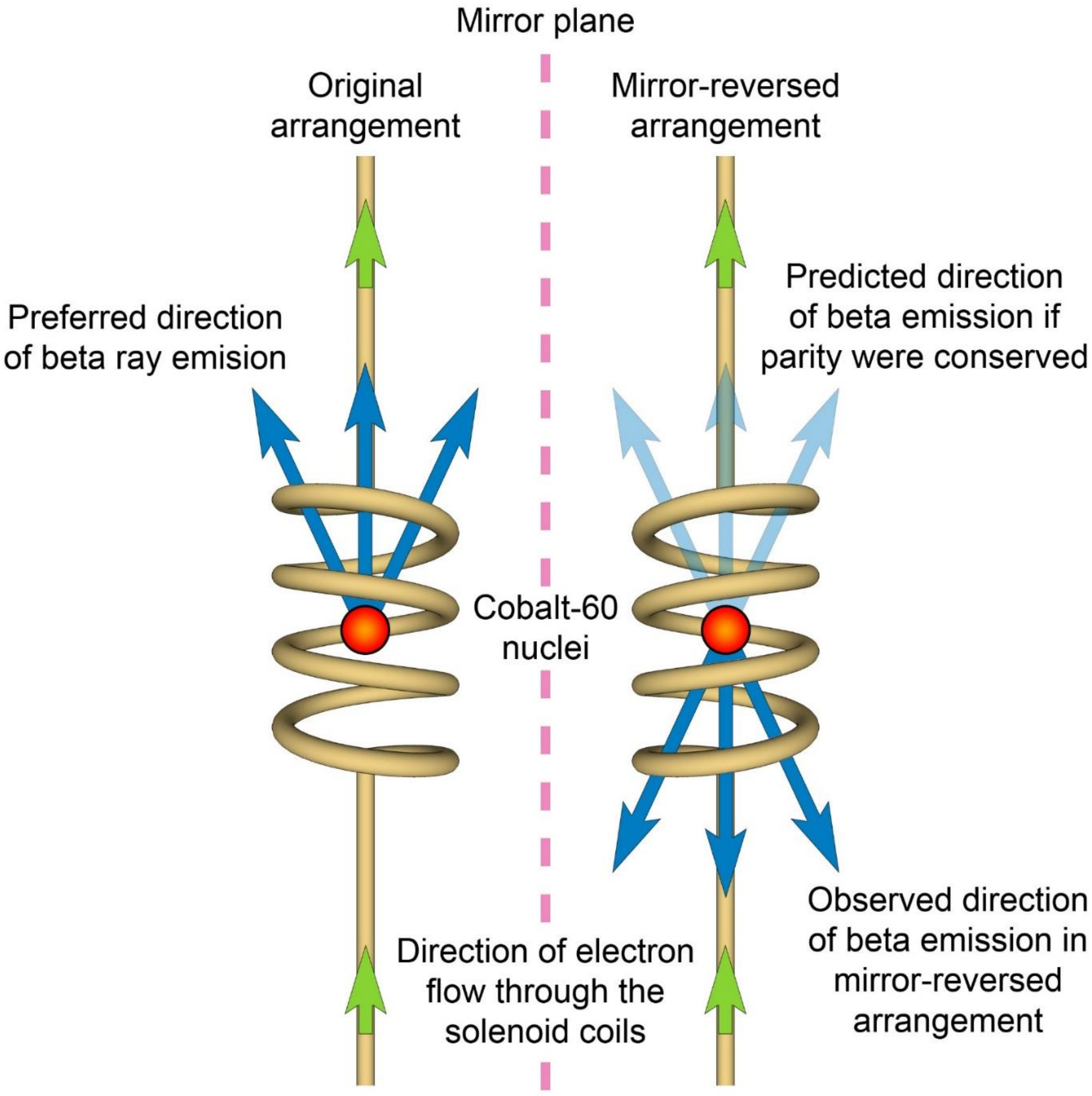


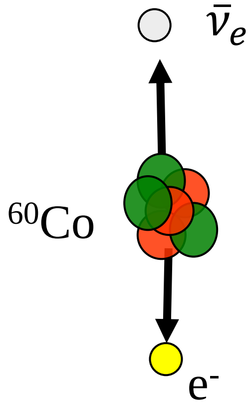
Process:

$$60Co \rightarrow 60Ni + e^- + \nu_e$$

Beta decay violates parity

Parity Violation in nature in laws of physics





Process:

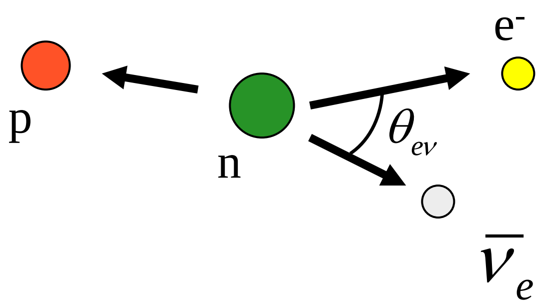
$$60Co \rightarrow 60Ni + e^- + \nu_e$$

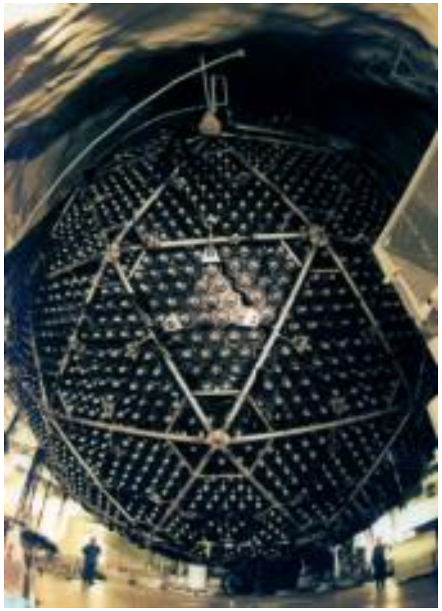
Beta decay violates parity

This kind of parity violation is fundamental. There are no other Co-60 atoms that behave differently. And there is no known process like evolution that could have selected one type of Co-60 atoms over the other.

Idea of the cos $\theta_{e\nu}$ spectrometer Nab @ SNS

$$dw \propto \left(1 + a \frac{p_e}{E_e} \cos\theta_{e\nu} \right)$$





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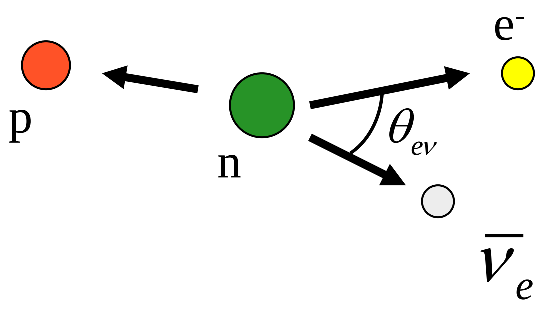

Kinematics:

- Energy Conservation: $E_\nu = E_{e,max} - E_e$
- Momentum Conservation

$$p_p{}^2 = p_e{}^2 + p_\nu{}^2 + 2p_e p_\nu \cos\theta_{e\nu}$$

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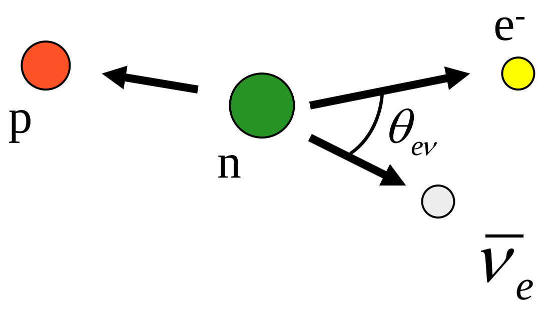

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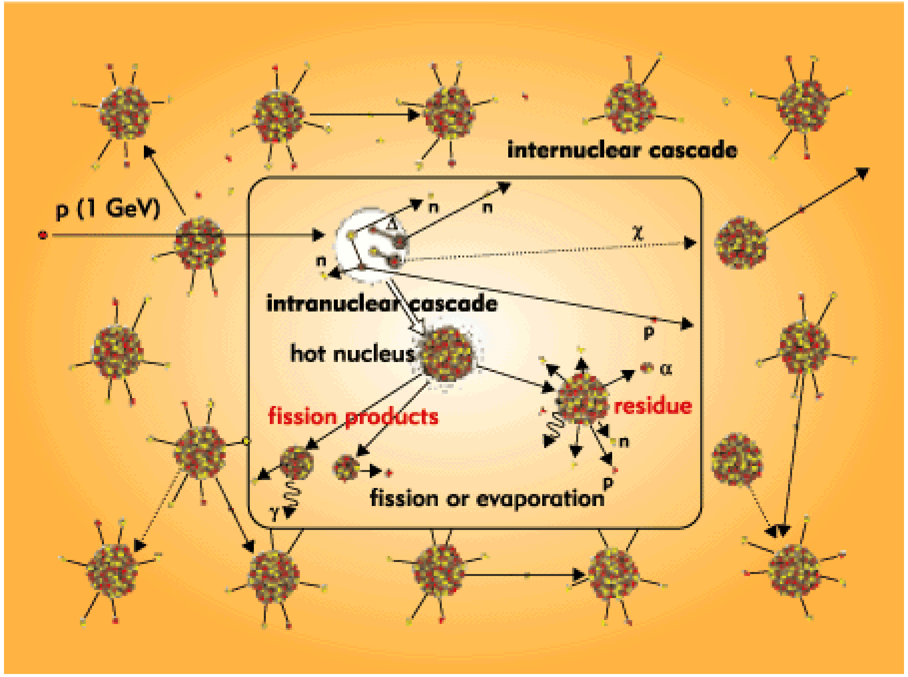
This is why you study kinematics with billiard balls in PHYS1710 right now! ☺

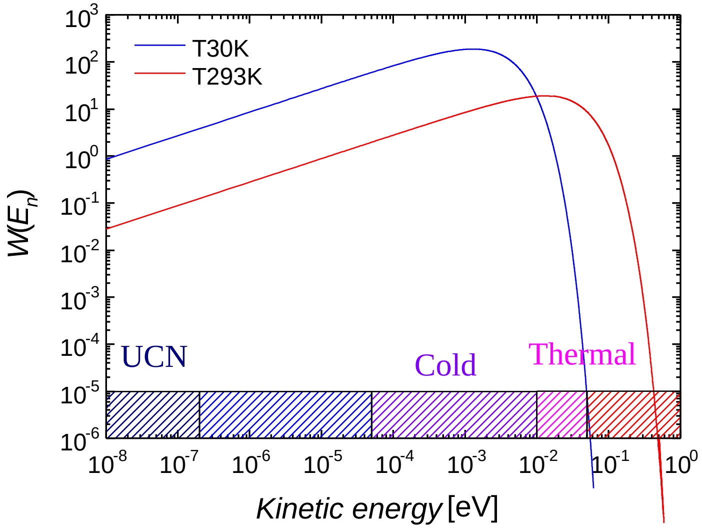
The Spallation Neutron Source SNS in Oak Ridge, TN

Production of free neutrons



Neutron production in a spallation source

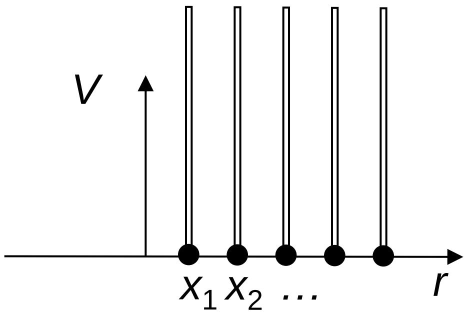
Neutron moderation



One-minute phenomenology of Cold Neutrons

Interaction potential between low energy neutrons and matter (that is: The nuclei in matter):

$$V_{\mathrm{Fermi}} = \frac{2\pi\hbar^2}{m_{\mathrm{n}}} \sum_{\mathrm{nuclei}} b_{\mathrm{nucleon}} \delta(x - x_i)$$



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$$\lambda = h / m_{\mathrm{n}} v$$

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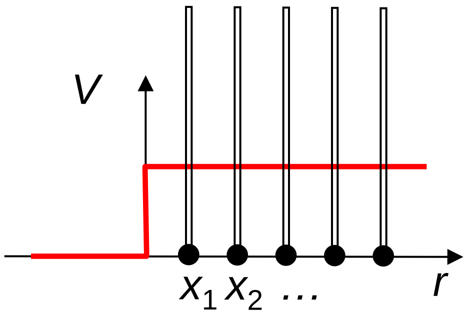

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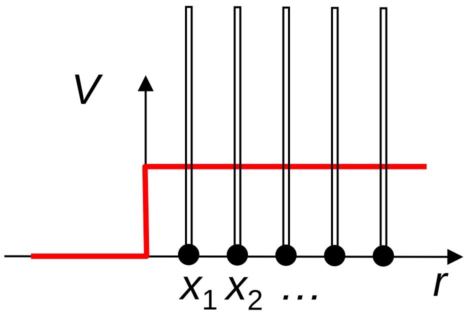

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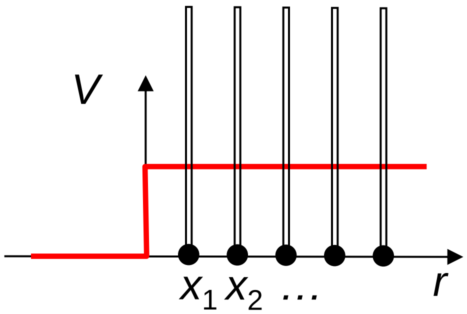

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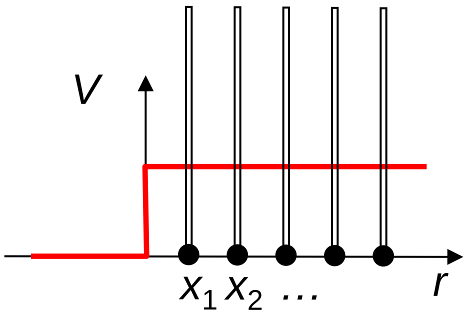

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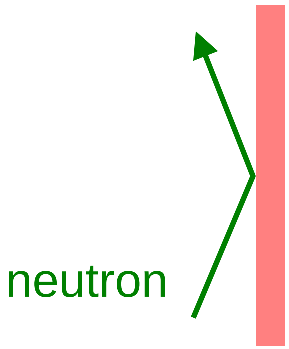
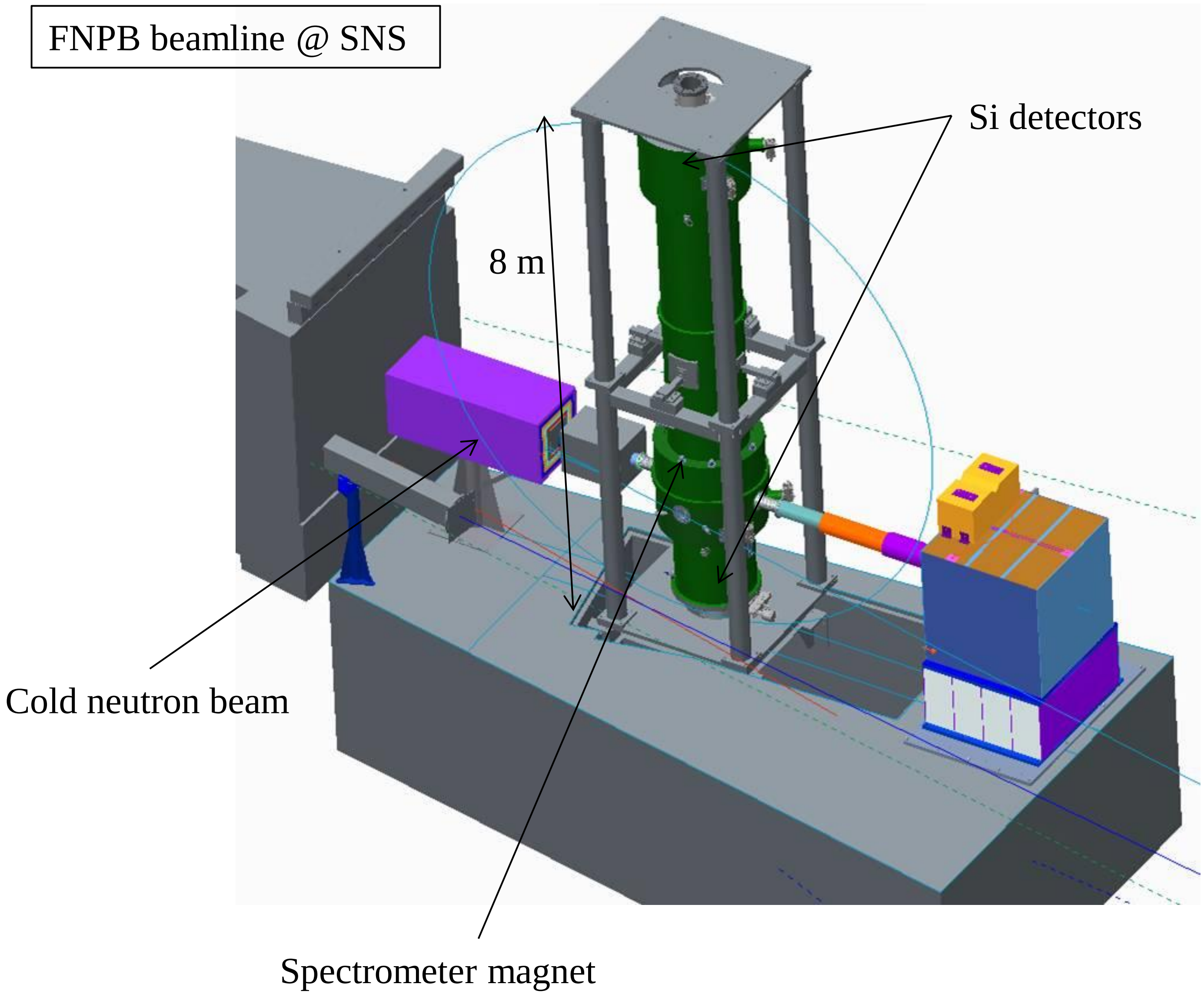
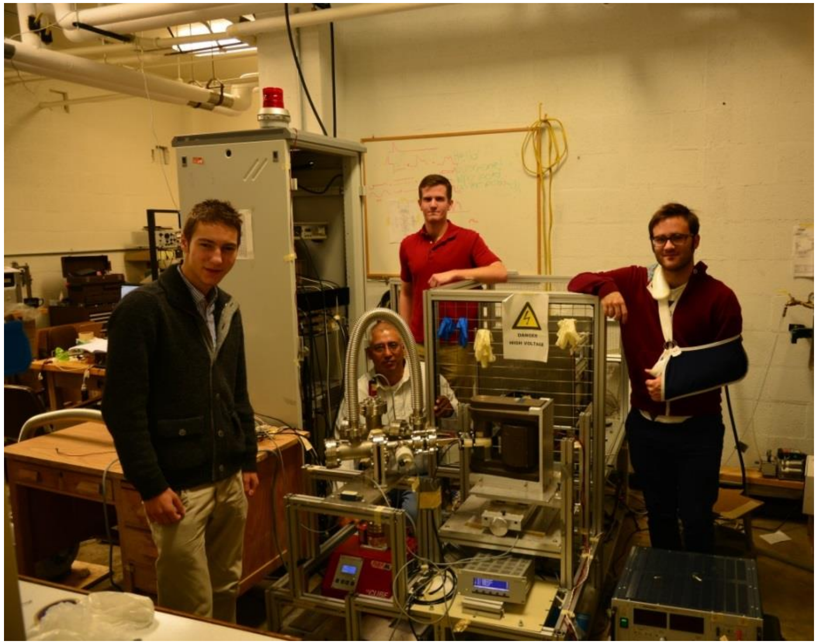


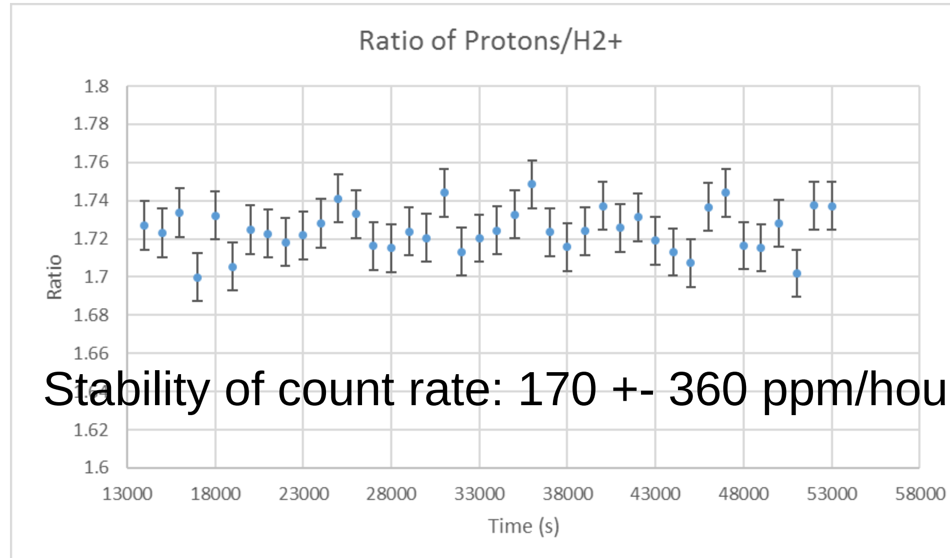
Nab setup at Spallation Neutron Source (SNS)



Proton source for detector tests (and lab)

Commissioning results:





Stability of count rate: 170 +- 360 ppm/hour

Proton source and detector team:

A. Ross (Mitchell fellowship), R. Slater, Z. Tompkins, A. Salas Bacci, P. Zotev, D. Pocanic, N. Roane, C.J. Whittaker, D. Warner, P. Carr, Sh. Zamperini, A. Smith, M. Doyle, C. Ries, A. Bryant, S.B. (all UVa)

M. Schlegel, J.-P. Burchert, F. Anastasopoulus (DAAD fellowships)

Electrode team)not discussed):

R. Hodges, H. Bonner, S. McGovern, Ch. Tong, B. Farrar, A. Smith, D. v.Petten, R. Mulherin, M. Allison, H. Li, J. Clement (all UVa), G. Konrad (TU Wien)

Simulations and Spectrometer design:

J. Brown, T. Niu, N. Roane, E. Frlez, P. Alonzi, D. McLaughlin, H. W. Fan, H. Li, E. Stevens, C. Lu, D. Pocanic, S.B.

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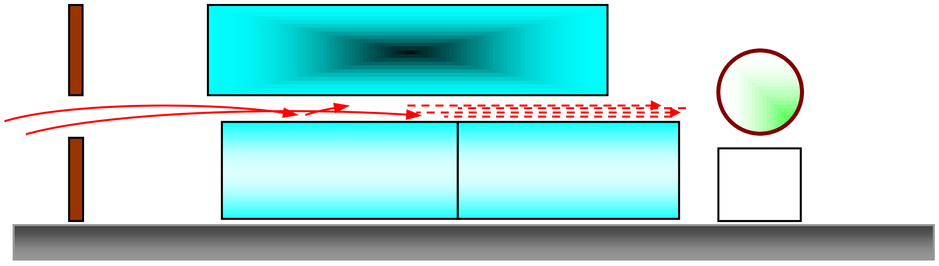

The neutron source of the ILL Grenoble/France

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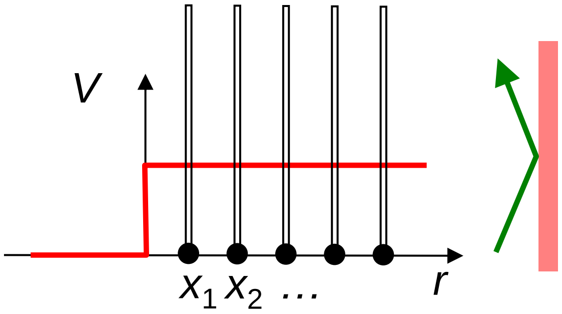

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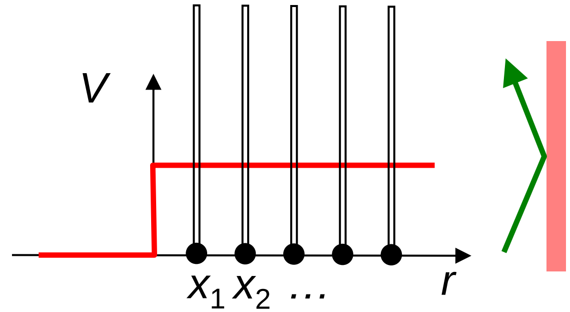

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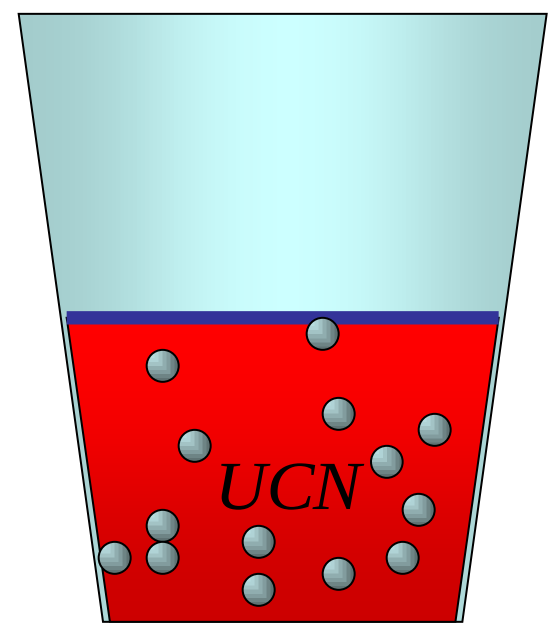
Ultracold Neutrons: (neutrons that reflect under all angles)

Energy: $E_{\text{UCN}} = \frac{m_{\text{n}}}{2} v_{\text{UCN}}{}^2 \lesssim V_{\text{Fermi}} = 100 \text{ neV}$

Velocity: $v_{\text{UCN}} \lesssim 5 \text{ m/s}$

Height in gravitational field: $h_{\text{UCN}} = \frac{E_{\text{UCN}}}{m_{\text{n}} g} \lesssim 1 \text{ m}$



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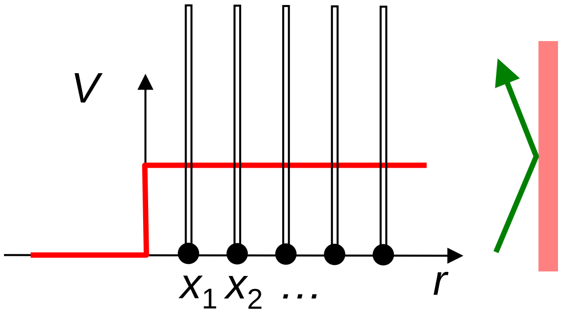

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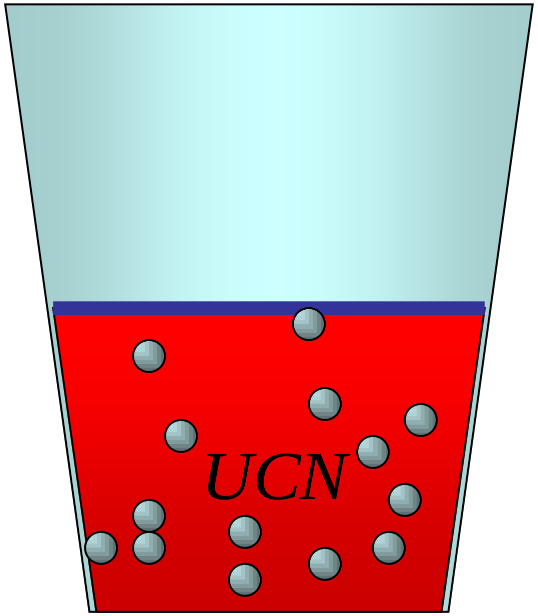
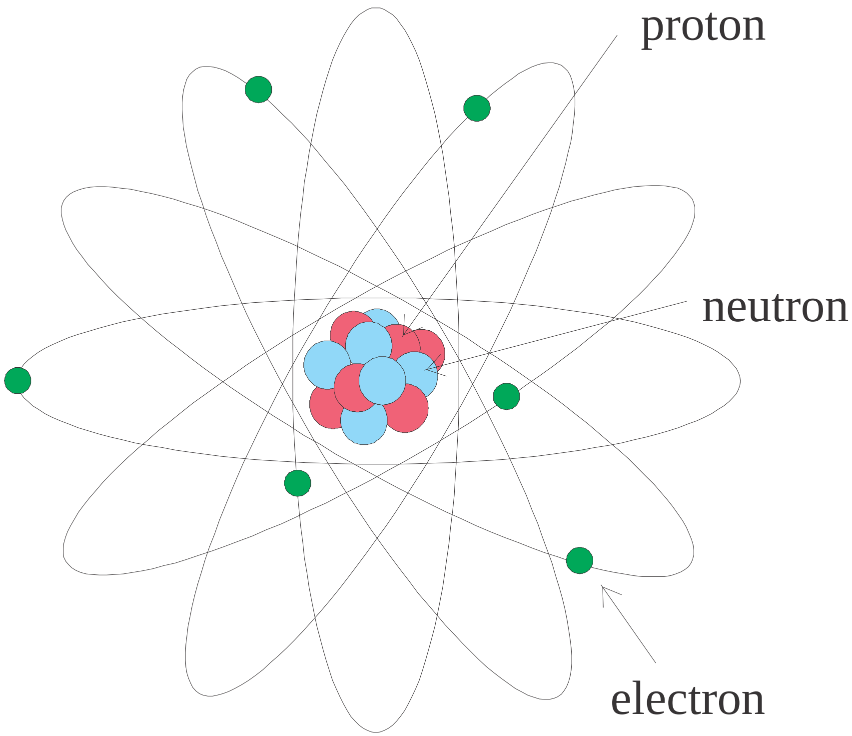
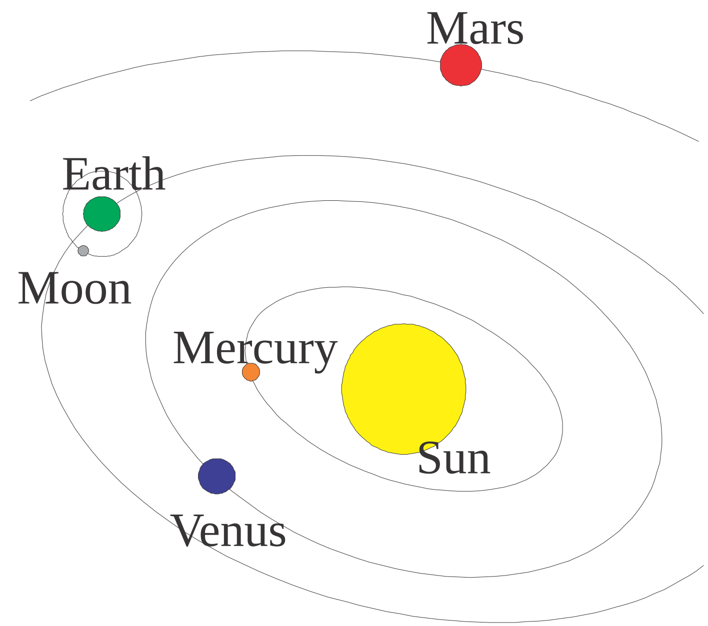


Main usage: Precision measurements for fundamental physics

- Neutron beta decay
- Electric Dipole Moment

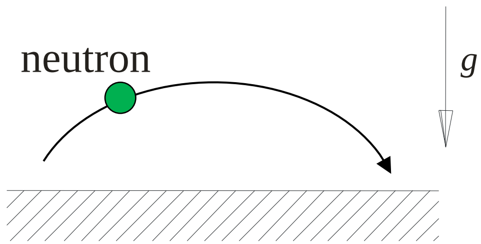
Gravitationally bound quantum states



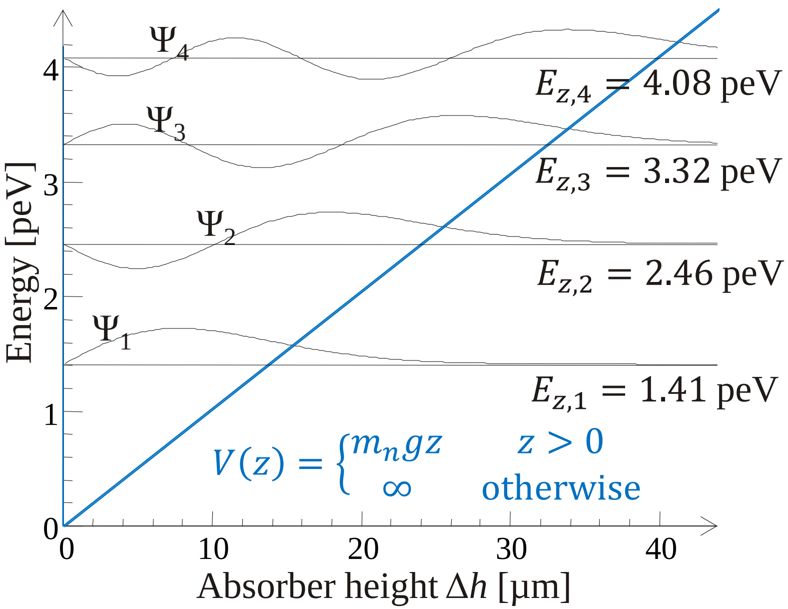


- Electrons in an atom tend to be found in the lowest accessible state.
  → Relaxation / de-excitation is fast.
- Planets in the Solar System are in a superposition of quantum states with very high quantum numbers. And stay there.
- If gravity was much stronger, planets on their orbit would loose energy while emitting gravitons.

Gravitationally Bound states – The idea



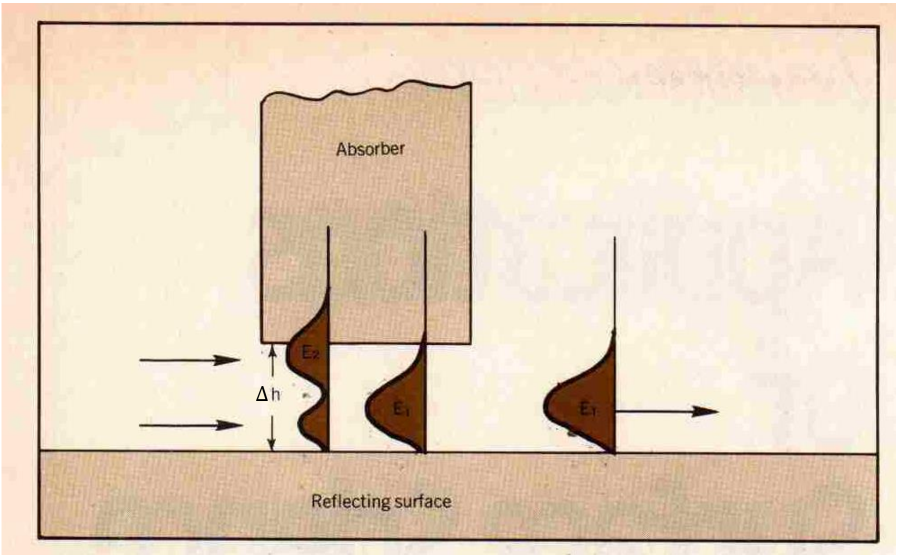
Quantum mechanics: Energy of neutron is quantized!



$$-\frac{\hbar^2}{2m_\mathrm{n}}\frac{\partial^2}{\partial z^2}\Psi(z) + V(z)\Psi(z) = E_z\Psi(z)$$

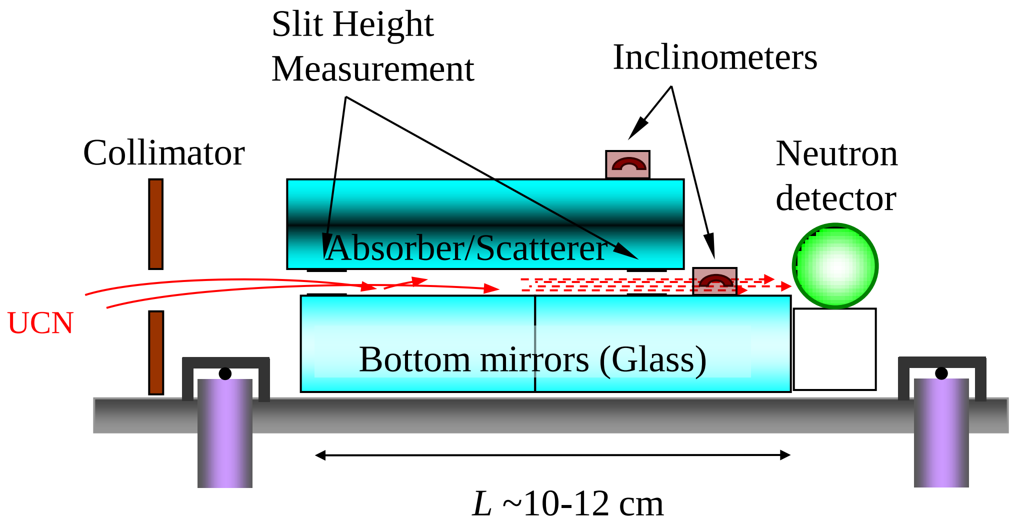
$$\Psi_k(z) \propto \mathrm{Ai}\left(\frac{z-z_k}{l_0}\right);\ z_k = l_0 \cdot \lambda_k;\ \ E_{z,k} = m_n g l_0 \cdot \lambda_k$$

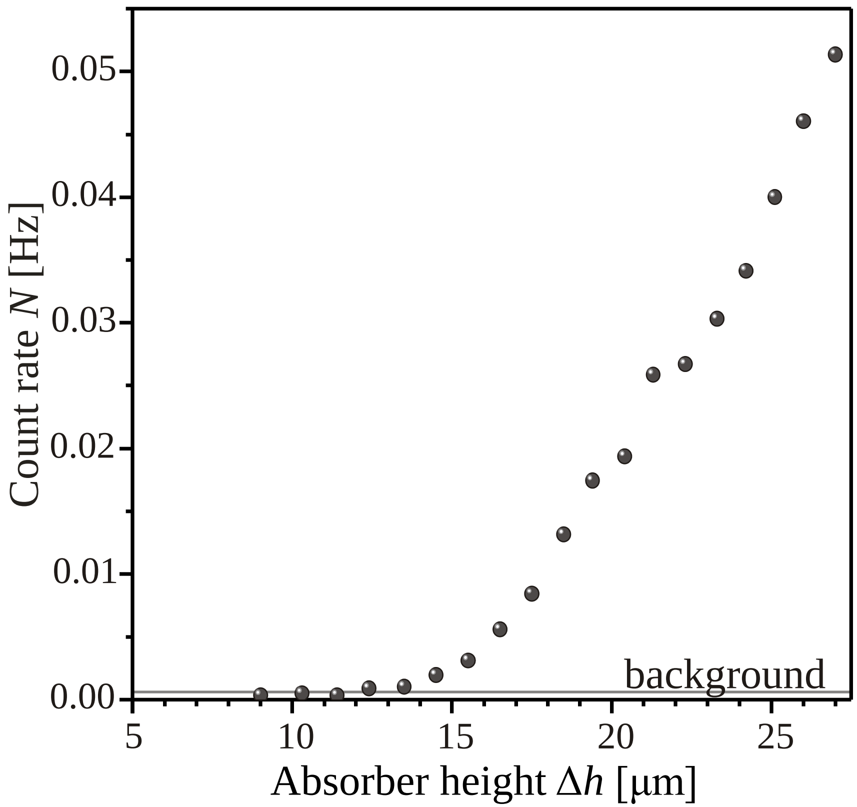
with $l_0 = \sqrt[3]{\hbar^2/2m_n^2 g} = 5.87$ μm, and the roots of the Airy function, $\lambda_k = 2.34, 4.09, 5.52, 6.79, \ldots$



V.I. Lushikov,
Physics Today, June 1977

Detection of the size of the quantum states





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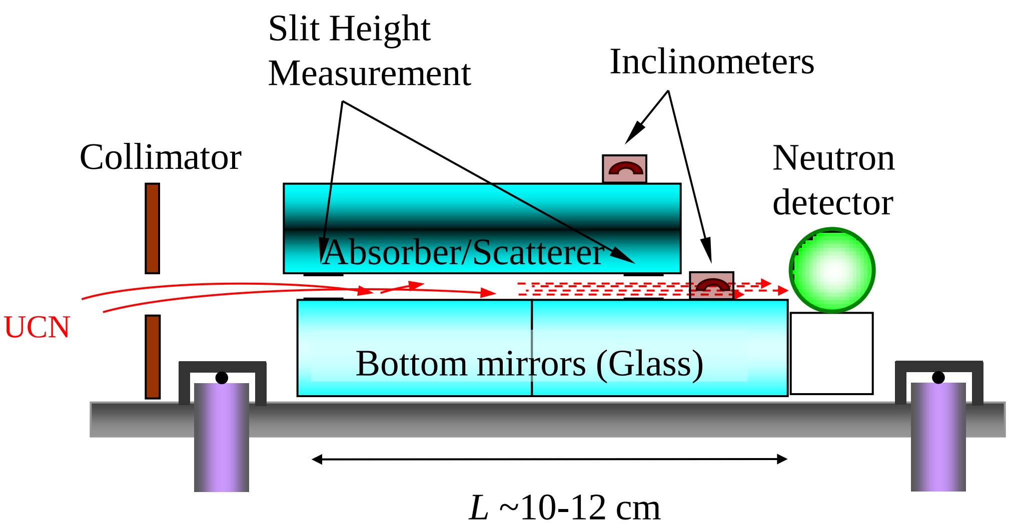
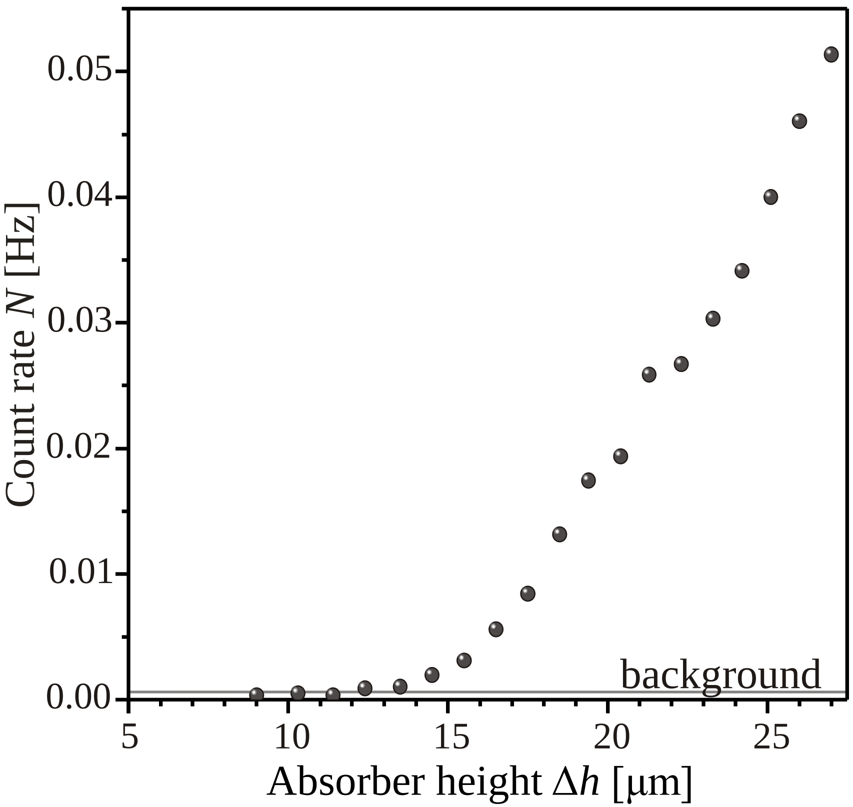
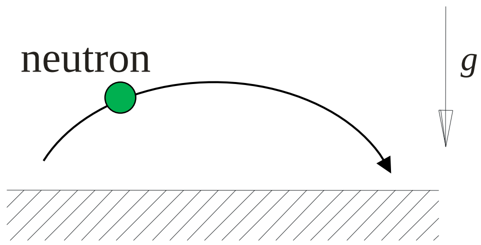




Motivation:

Search for new spin-dependent or spin-independent short-range forces (between neutron and the mirror and/or scatterer). Dark matter or dark energy models make testable predictions.

Gravitationally Bound states – The idea



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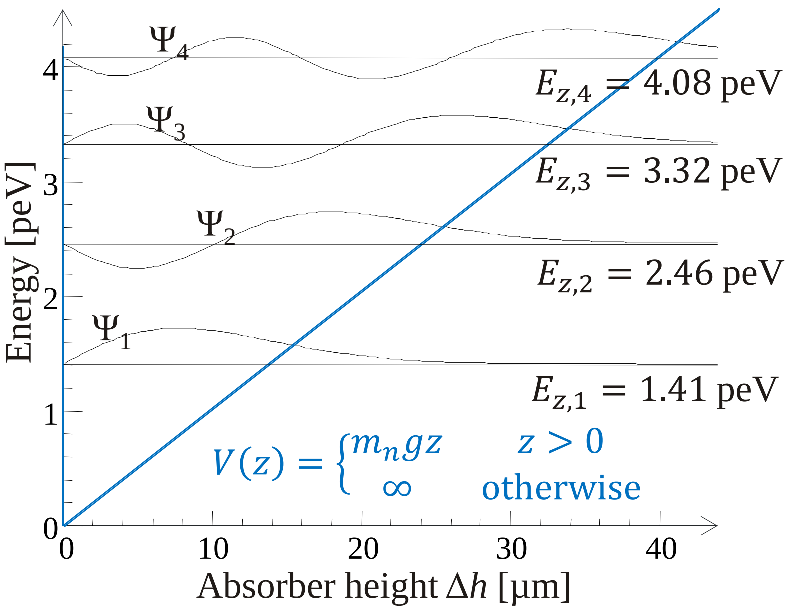
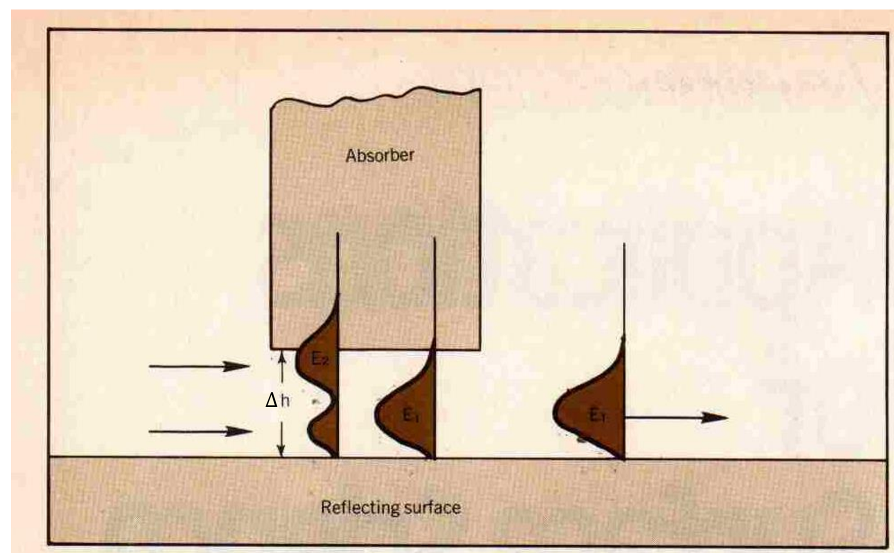
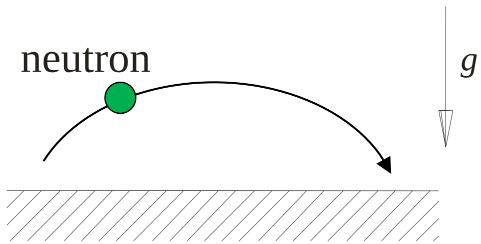
with $l_0 = \sqrt[3]{\hbar^2/2m_n^2 g} = 5.87$ μm, and the roots of the Airy function, $\lambda_k = 2.34, 4.09, 5.52, 6.79, \ldots$





V.I. Lushikov,
Physics Today, June 1977

Gravitationally Bound states – The idea



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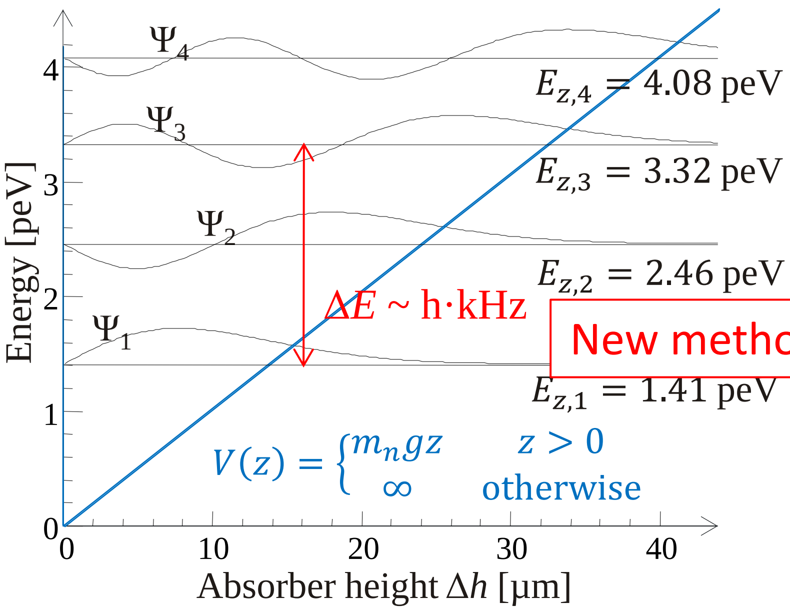
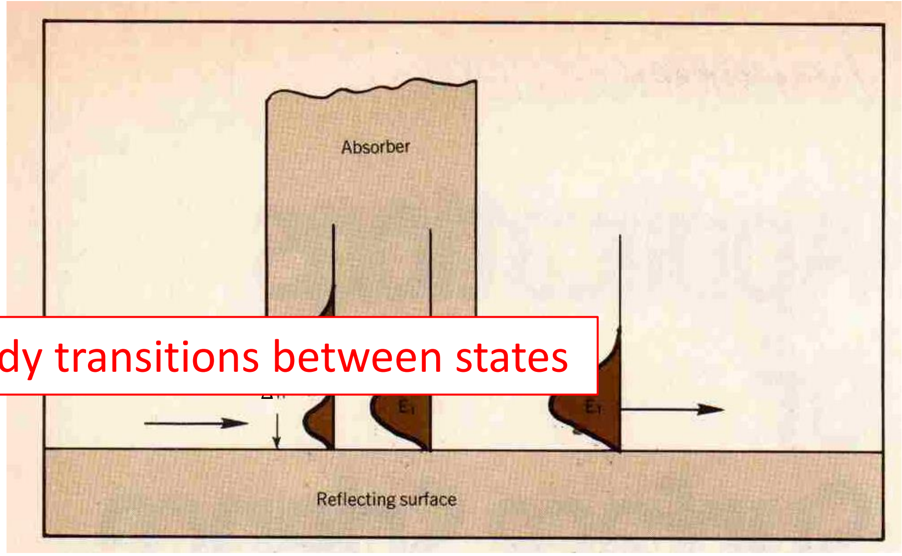


New method: Study transitions between states



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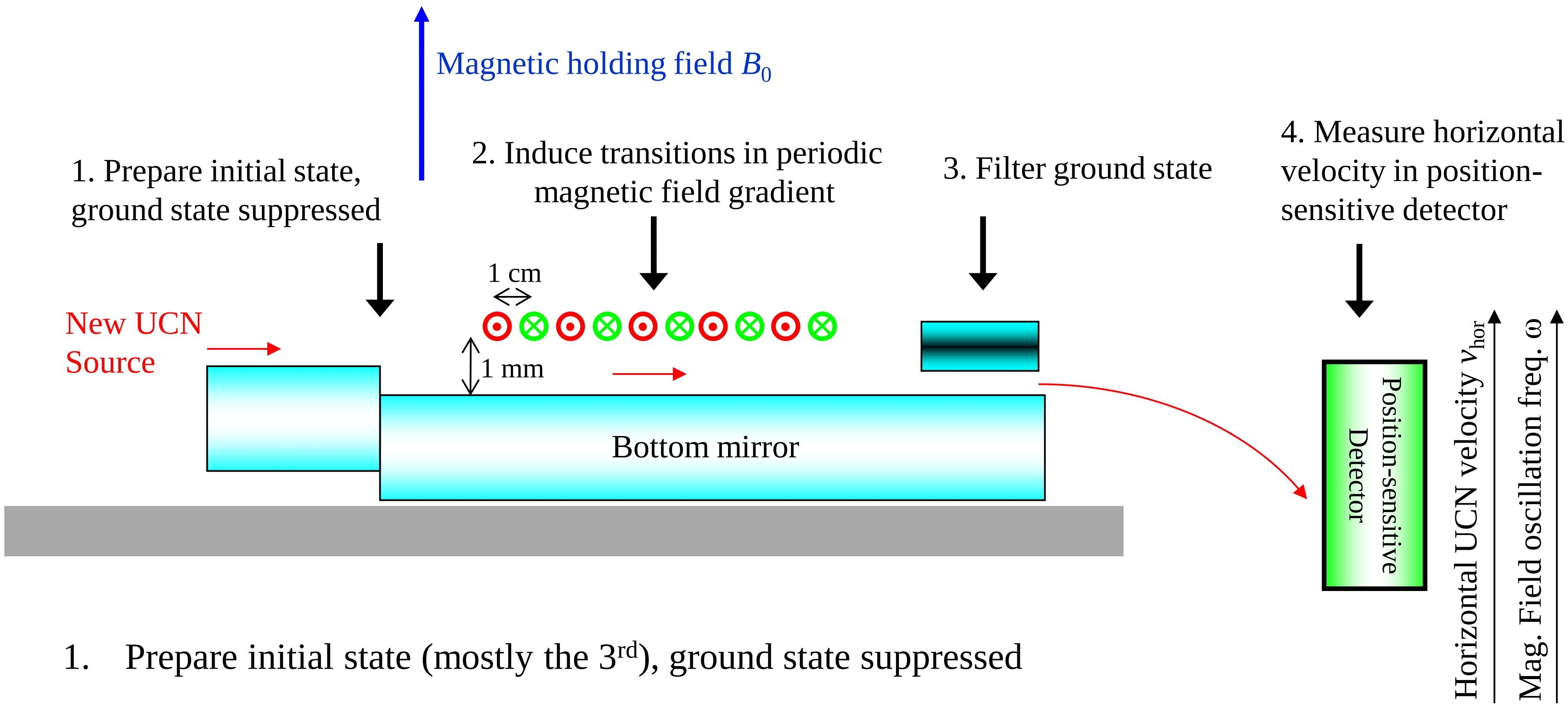
Physics Today, June 1977

First setup to detect magnetically induced resonance transitions in flow-through mode



1. Prepare initial state (mostly the 3rd), ground state suppressed
2. Induce Transitions 3→1 in time-dependent magnetic field gradient
3. Filter ground state
4. Detect neutrons in dependence of free fall height

   (corresponding to horizontal velocity, corresponding to oscillation frequency)

UVa contributions

Most recent:

- Spin filter (Louis Lukaczyk, Brianna Hogan*)
- Film detector for ultracold neutrons (M. Maloney, C. Ries)

*) Undergraduate research prize

If interested:
Stefan Baessler
Physics department, rm 169
434 243 1024
Baessler@Virginia.edu