Neutron Physics

W. M. Snow
Physics Department
Indiana University
NPSS, Bar Harbor

5 lectures:

1. Physics/Technology of Cold and Ultracold Neutrons
2. Electroweak Standard Model Tests [neutron beta decay]
3. Nuclear physics/QCD [weak interaction between nucleons]
4. Physics Beyond the Standard Model [EDM/T violation, B]
5. Other interesting stuff that neutrons can do [NNN interaction, searches for extra dimensions,…]

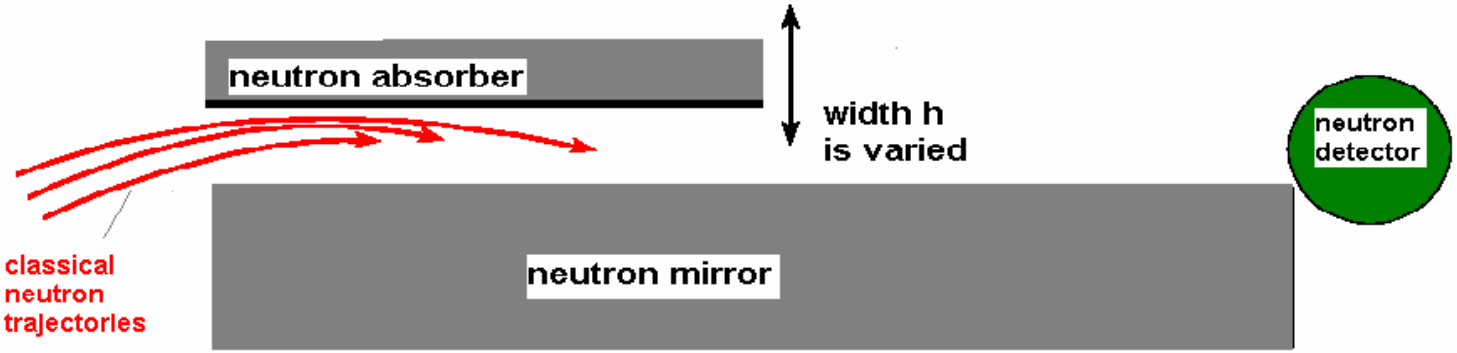
Other Interesting Physics

1. Neutron Gravitational Bound States
2. Precision Few-Nucleon Physics: n-A scattering lengths
3. T violation in Polarized Neutron/Polarized Target Transmission
4. Bell's Inequalities and Entangled QM States

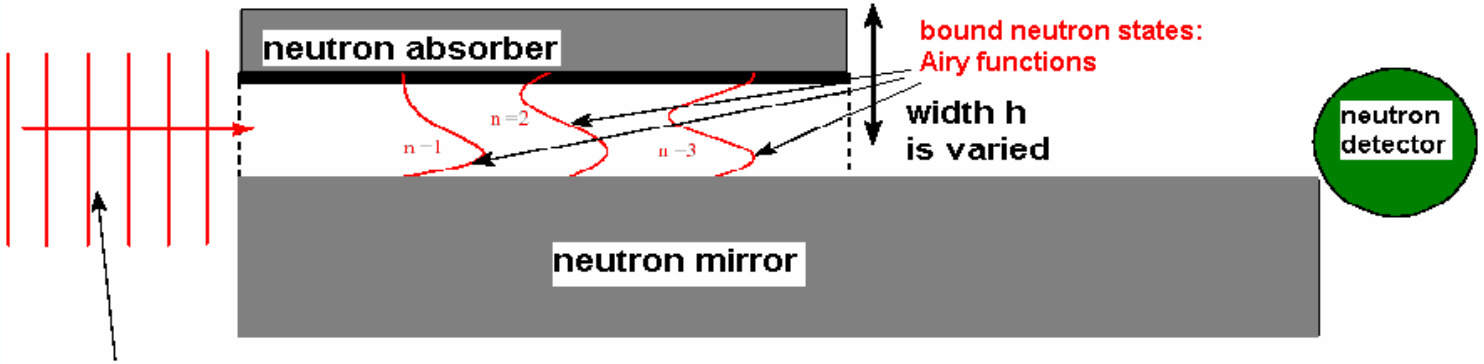
Thanks for slides to: Hartmut Abele (Heidelberg), Valery Nezvishevsky (ILL), Muhammad Arif (NIST), Tim Black (UNC/Wilmington), Yuji Hasegawa (Atominstitut, Wein)

Classical and QM Point of View

Classical View

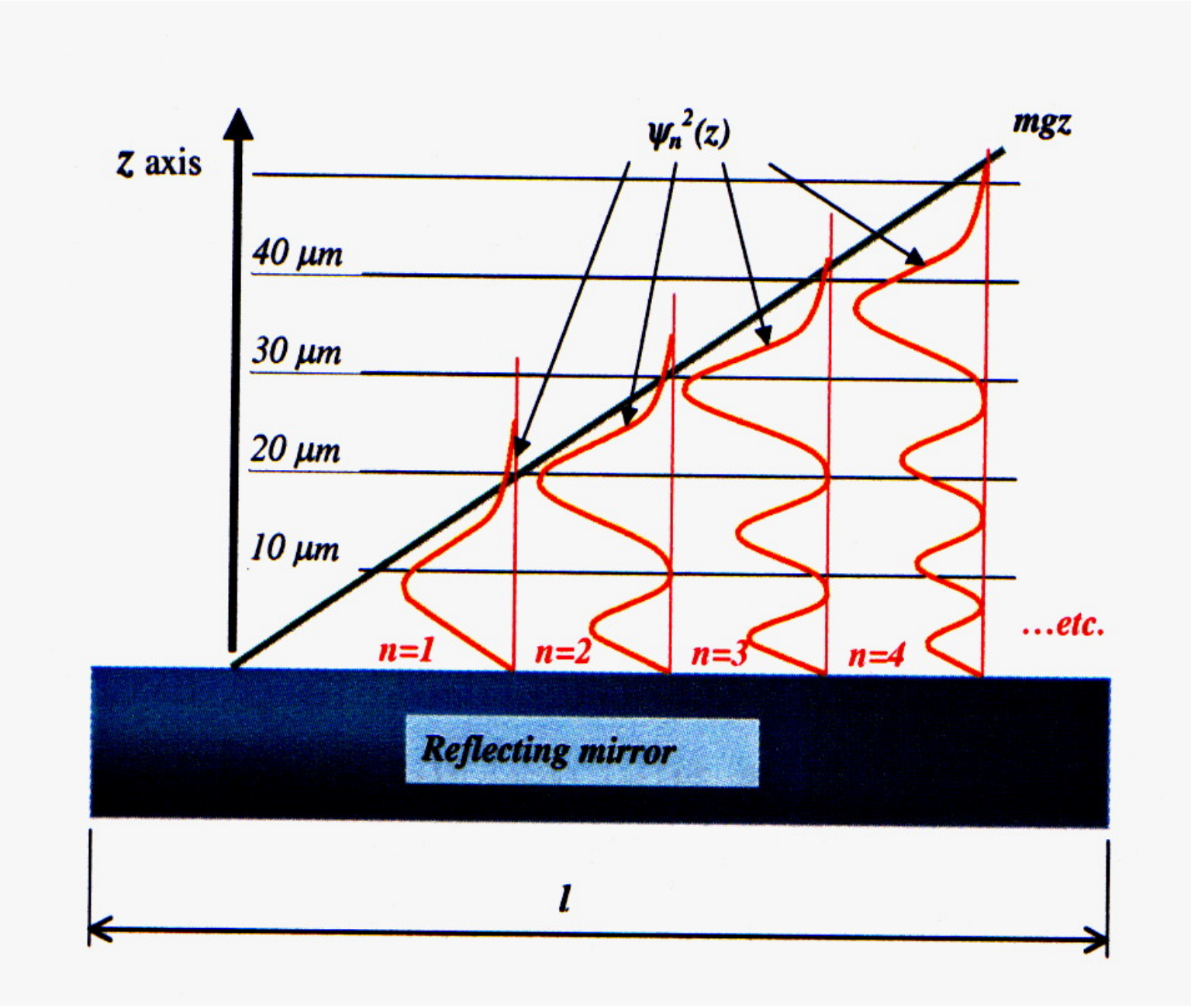


Quantum View

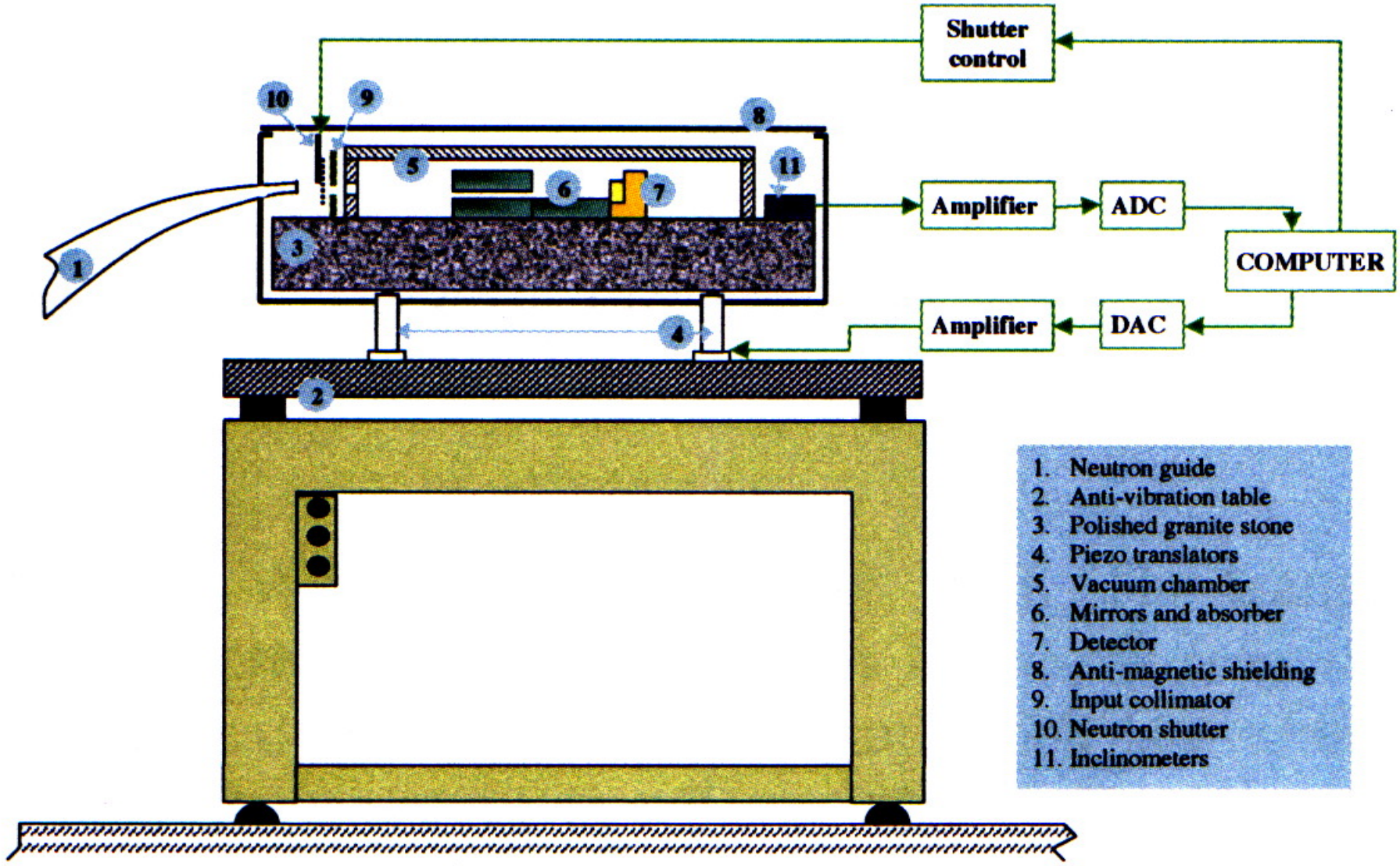


initial neutron state: plane wave

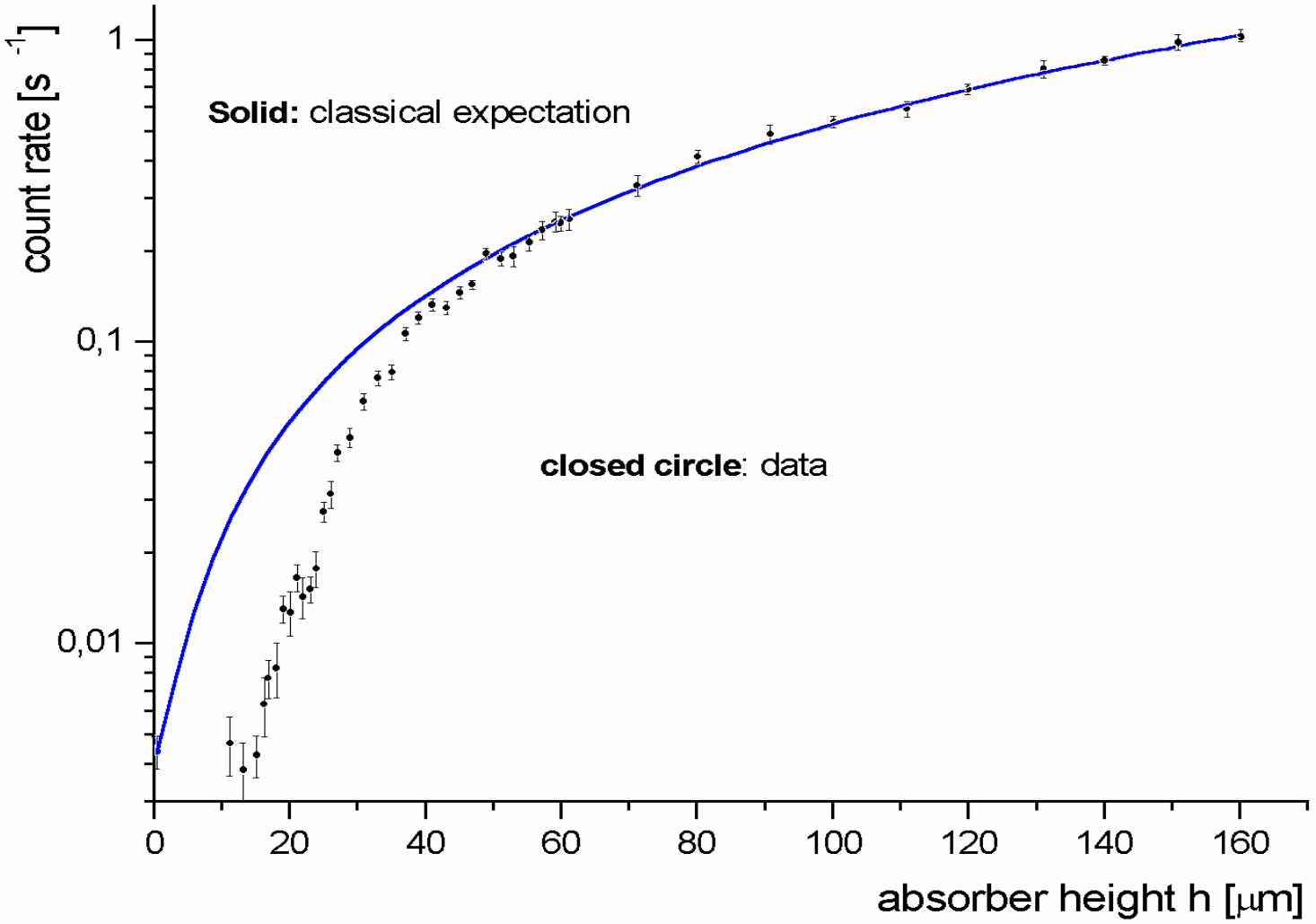
Neutron Probability Distributions Above the Mirror



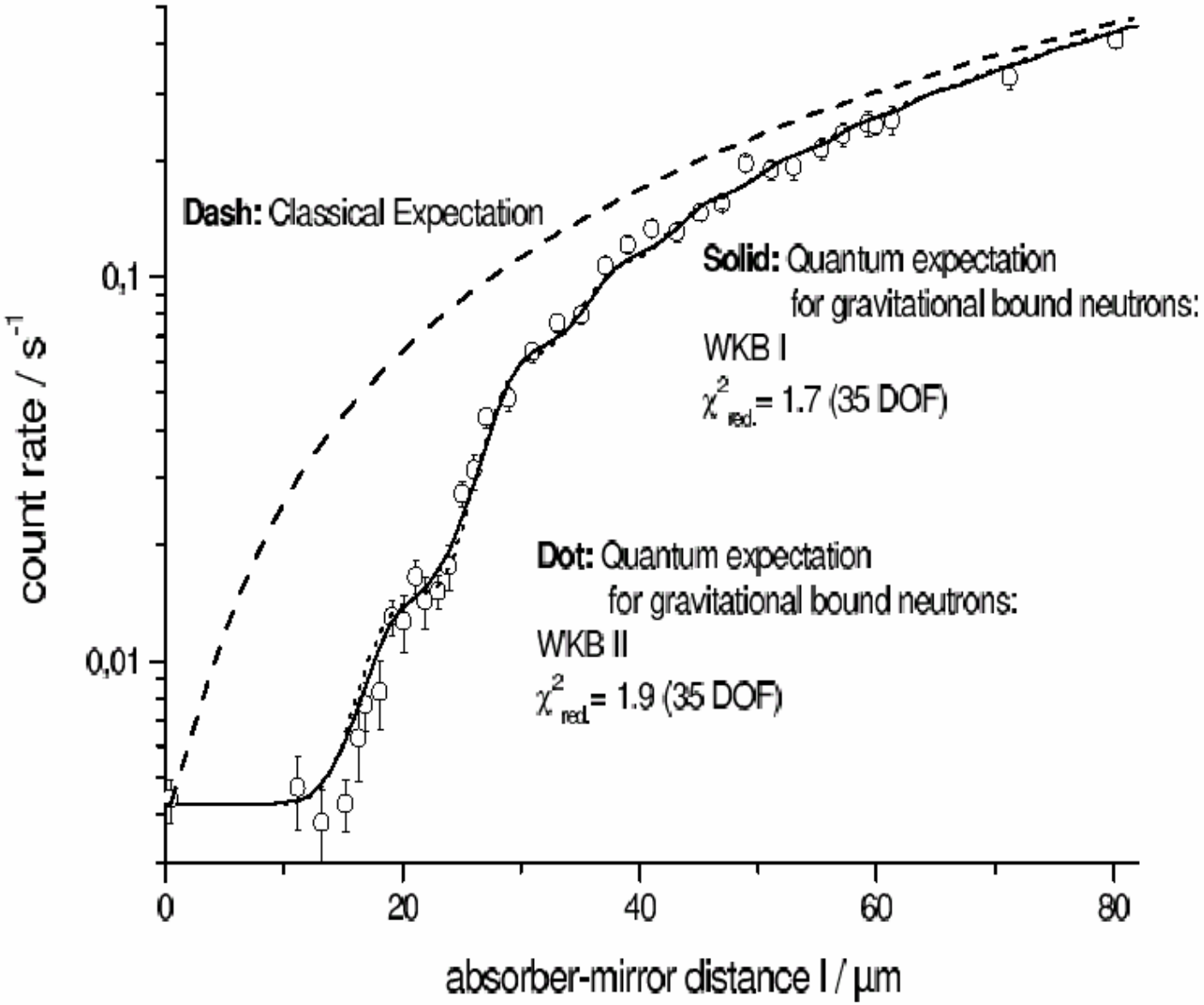
Experimental Apparatus



Observation of neutron gravitational quantum states



Comparison to Theory



Large extra dimensions?

- **Neutron, Newtonian**

$$g = \frac{Gm_E}{R_E^2} = \frac{4\pi \cdot G\rho R_E^3}{3R_E^2} \sim G\rho R_E$$

g = 9.85 ± 0.7 m/s^2

- **Non-Newtonian Interaction**

$$V(r) = -G\frac{m_i \cdot m_j}{r}(1 + \alpha \cdot e^{-r/\lambda})$$

- **Neutron, Non-Newtonian**

$$g\prime(z,\lambda) = 2\pi \cdot \rho\alpha\lambda G \cdot e^{-|z|/\lambda}$$

- **Ratio**

$$\frac{g\prime}{g}(z,\lambda) = \alpha \cdot \frac{\lambda}{R_E} \cdot e^{-|z|/\lambda}$$

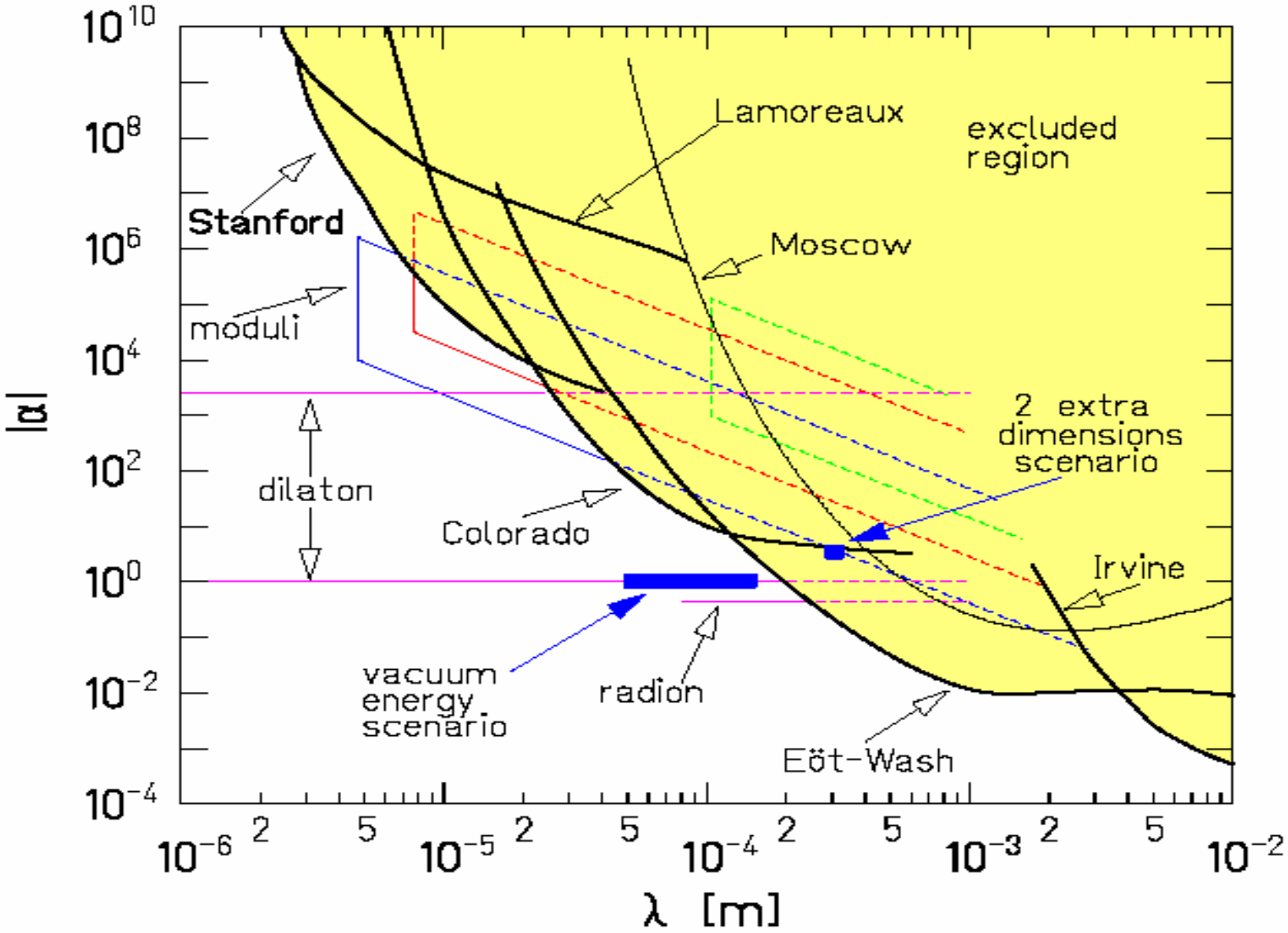
- **TeV scale Quantum Gravity:**

$$M_{Pl(4)}^2 = r_n^n M_{Pl(4+n)}^{n+2}$$

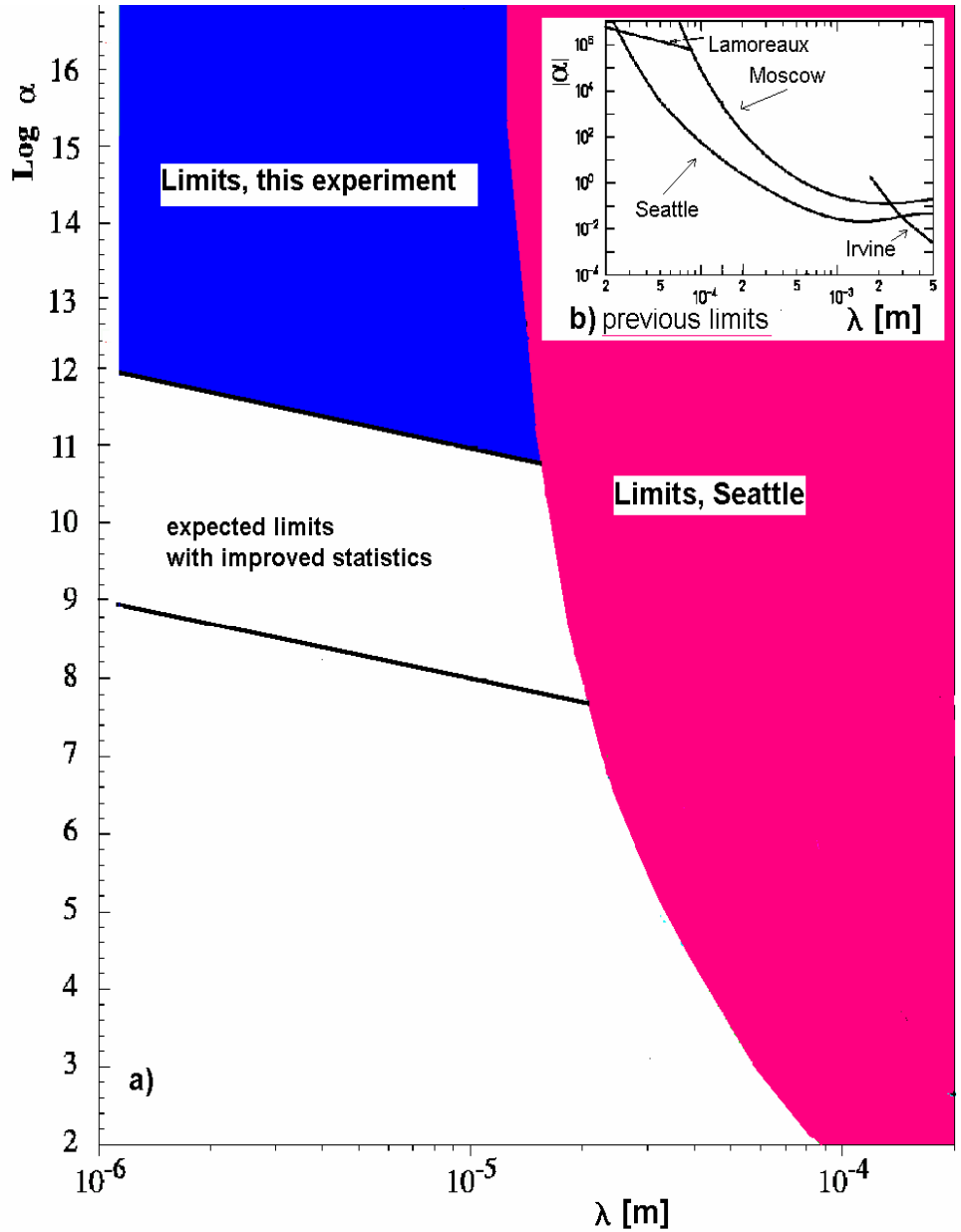
$$g_4^2 \sim \frac{1}{r_n^2 M_{(4+n)}^n} \sim \frac{M_{(4+n)}^2}{M_{(4)}^2}$$

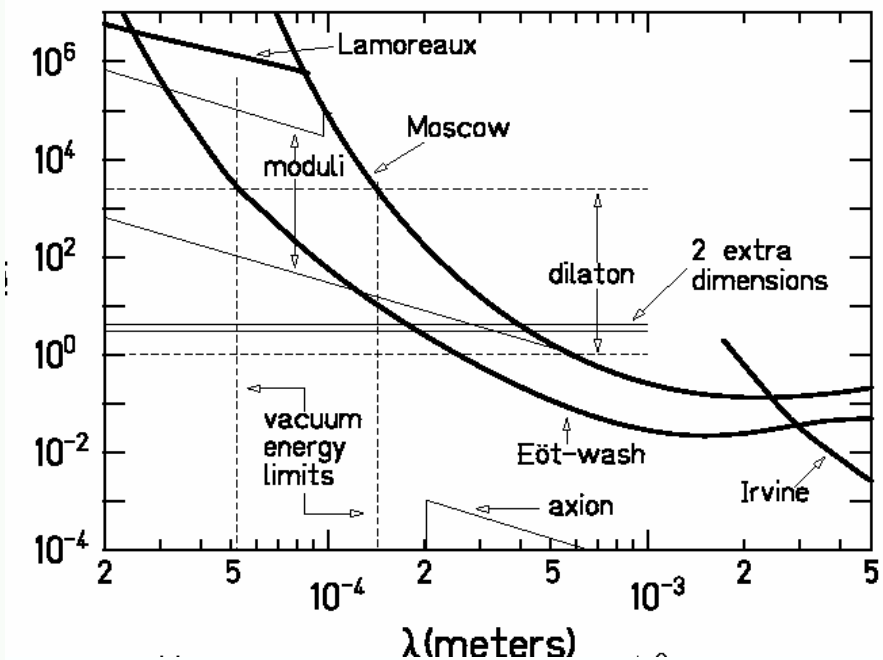
$$\frac{F_{gauge}}{F_{grav}} \sim \frac{g_4^2}{Gm_n^2} \sim 10^6 (\frac{g_4}{10^{-16}})^2$$

Previous Limits



Limits for alpha and lambda



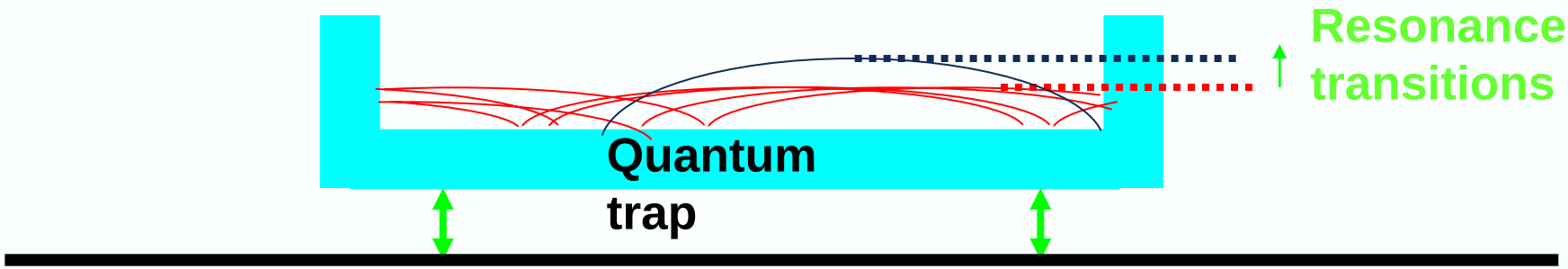


H. A. et al., Lecture Notes in Physics, Springer, 2003

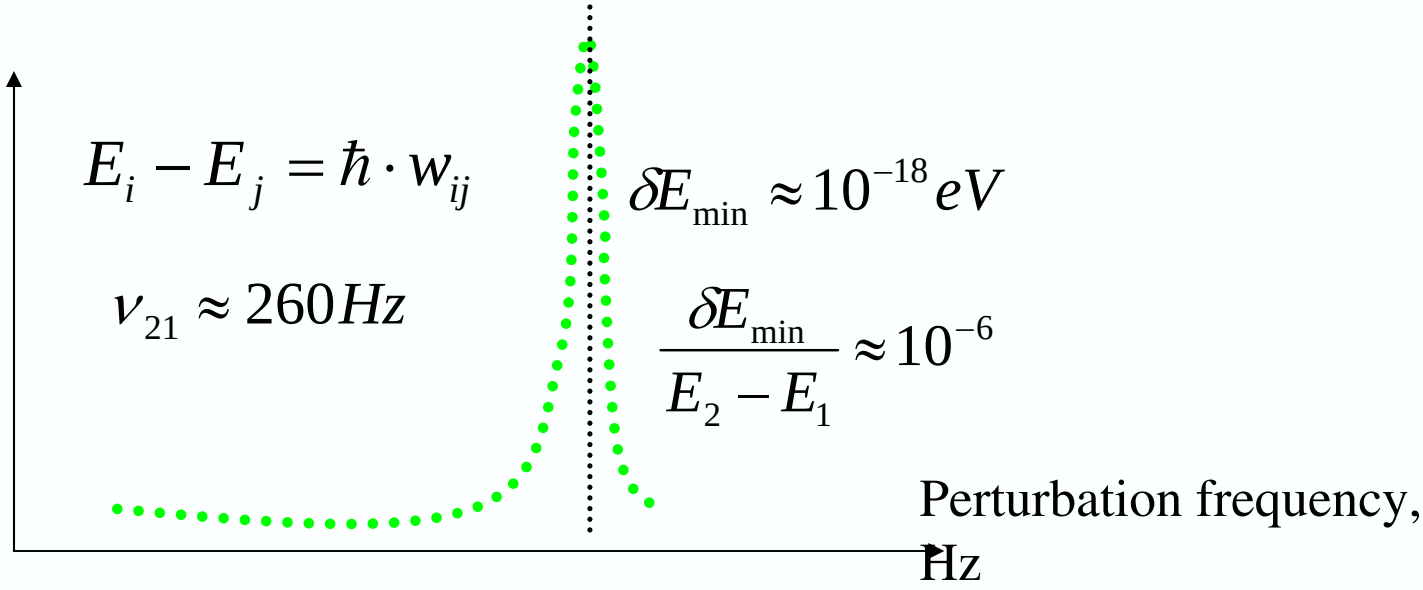
Potential Applications in fundamental physics

- Search for extra fundamental forces at short distances of 1 nm - 10 μm

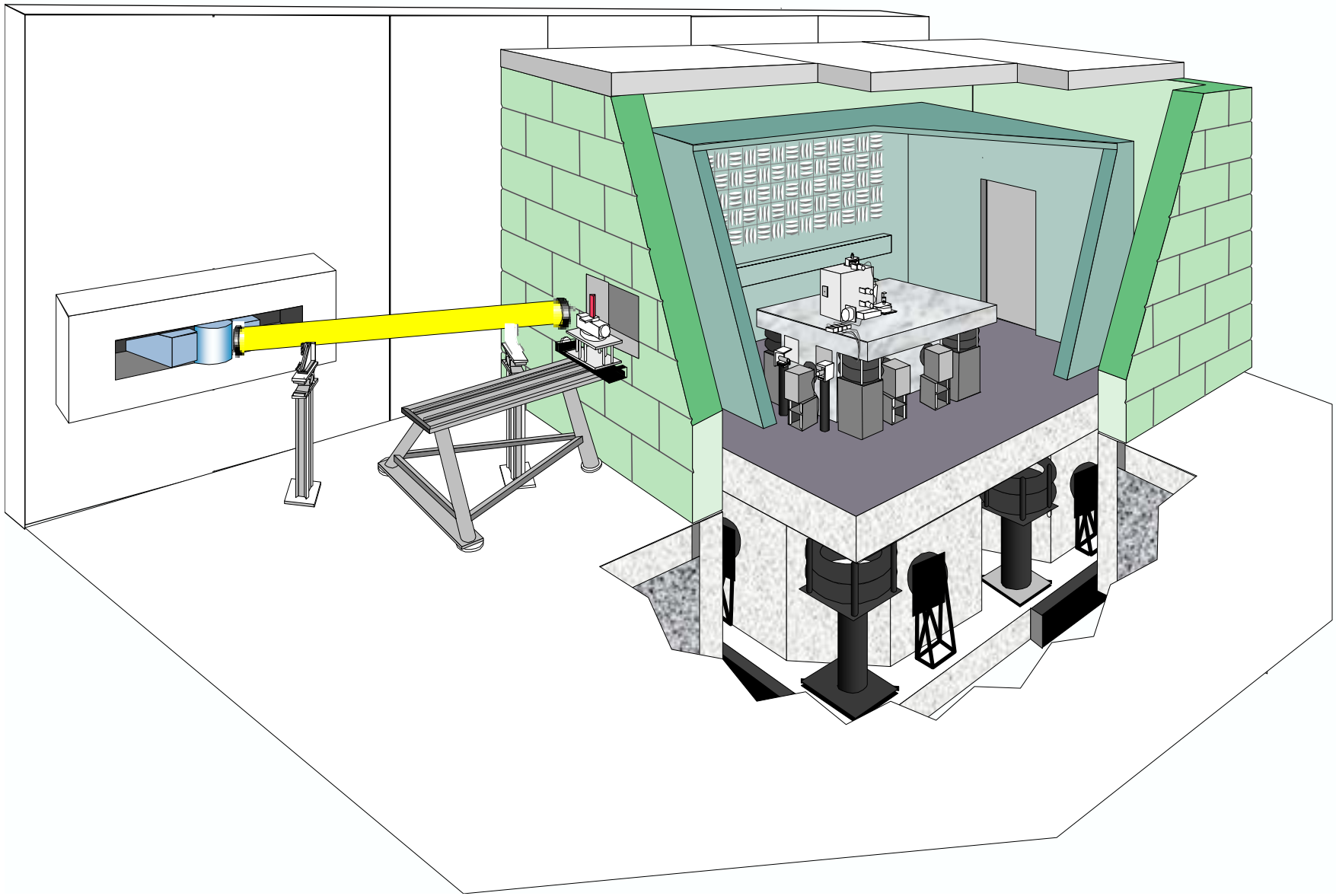
-Verification of electrical neutrality of neutrons



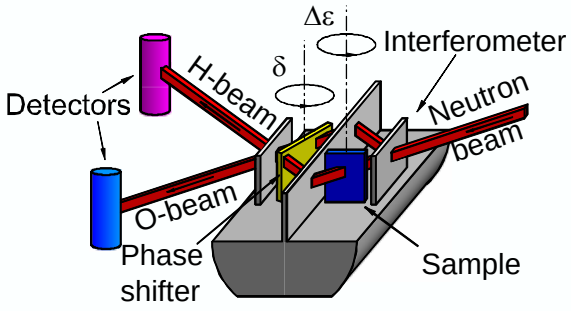
Transition probability induced by vibrating mass

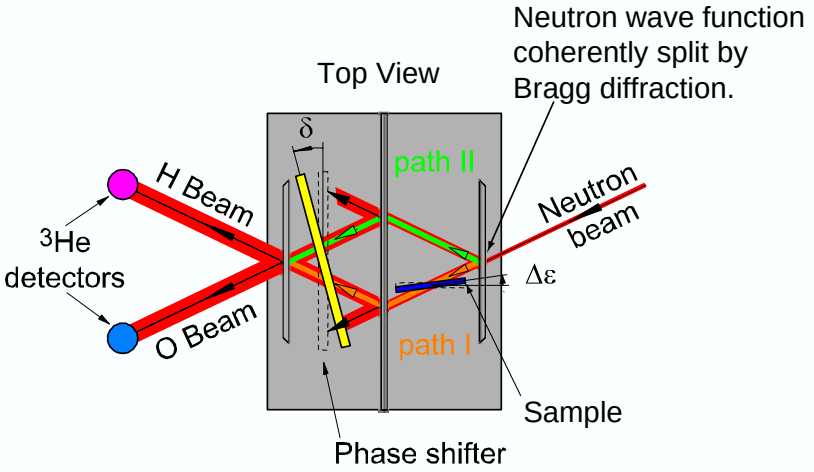


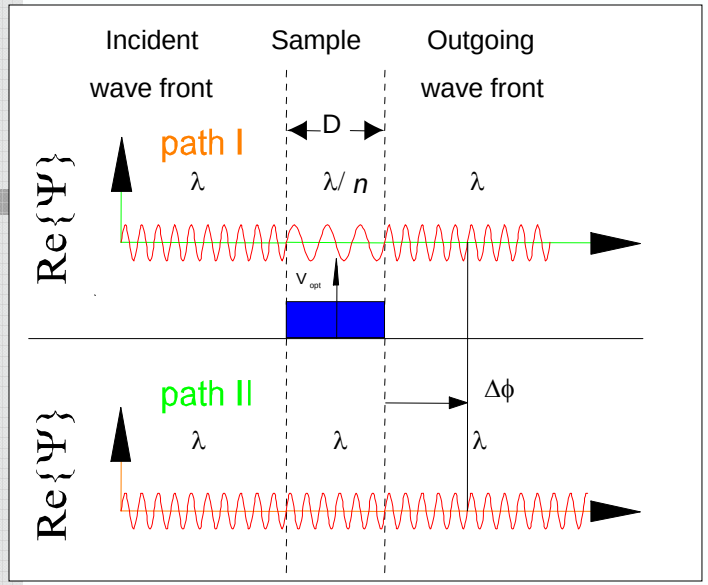
Neutron Interferometer and Optics Facility (NIOF) at NIST

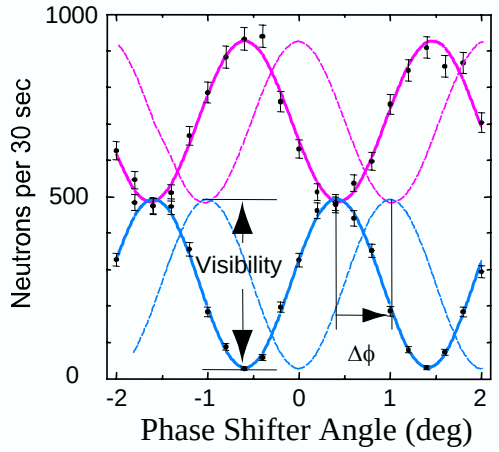


How a neutron interferometer works





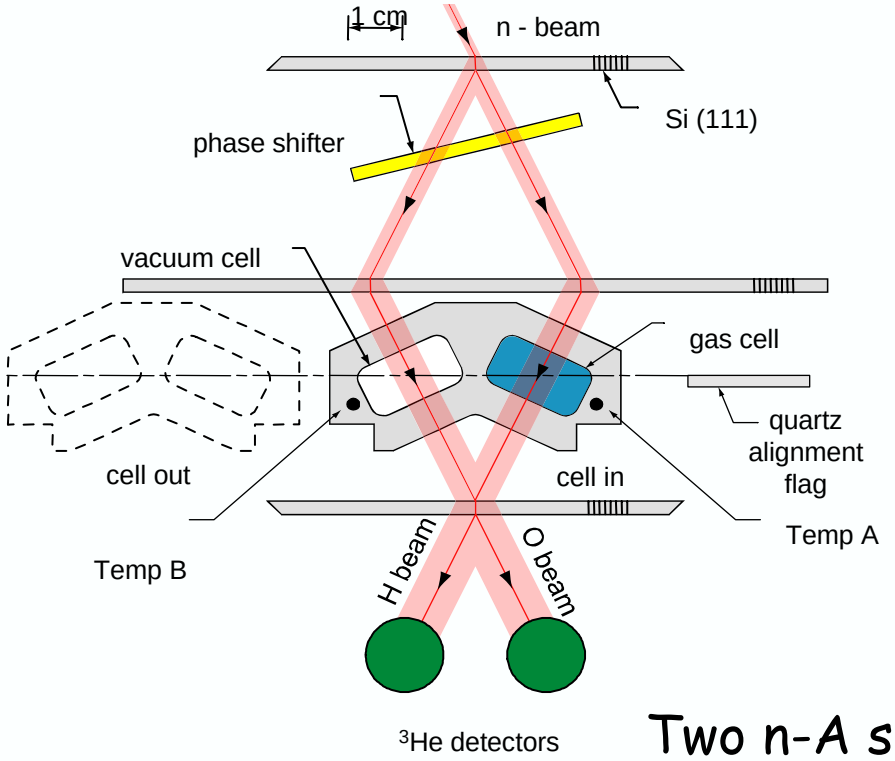


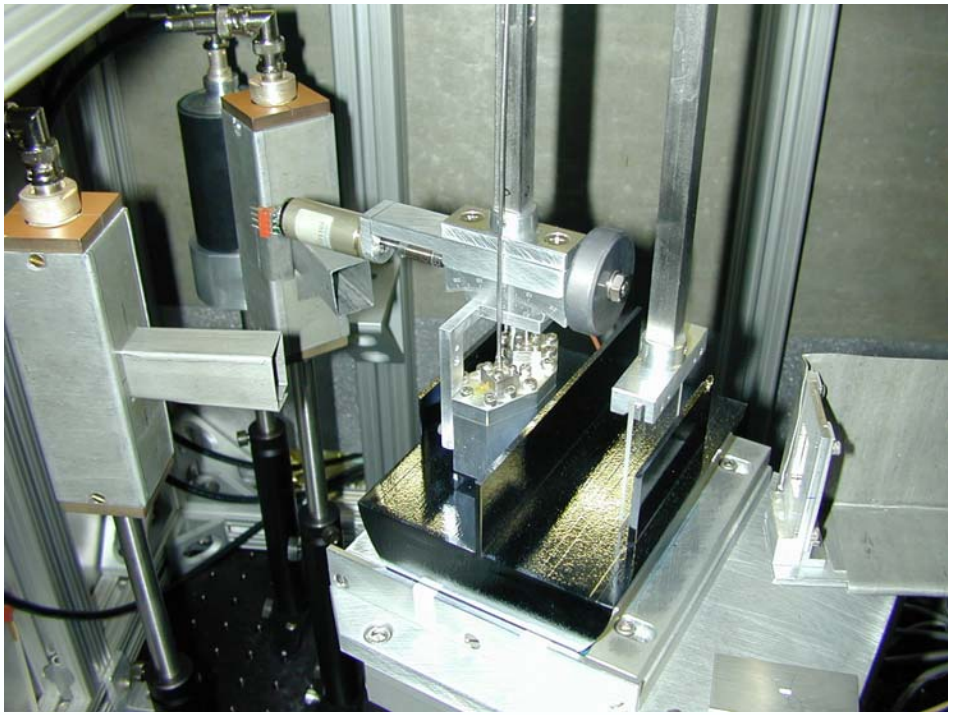


$$\Delta\phi = -\lambda N b D$$

- Visibility > 90%
- Only neutron optics device which can directly measure the phase shift.

Coherent Neutron scattering lengths





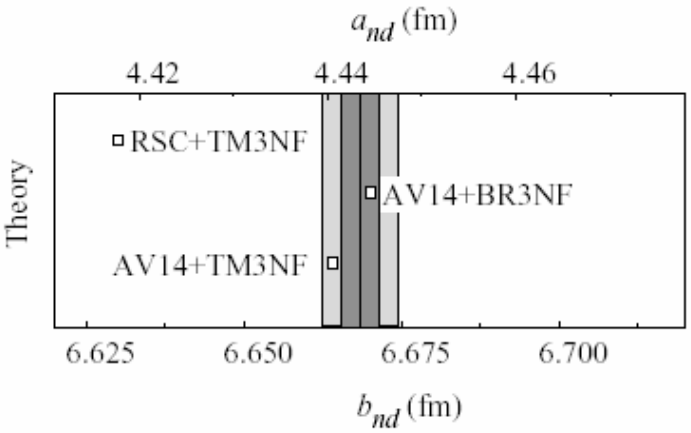
Two n-A scattering lengths $b_{\pm}$ for $I \pm 1/2$

Coherent scattering amplitude b_{coh}=sum over those amplitudes which do not change the QM state of the target

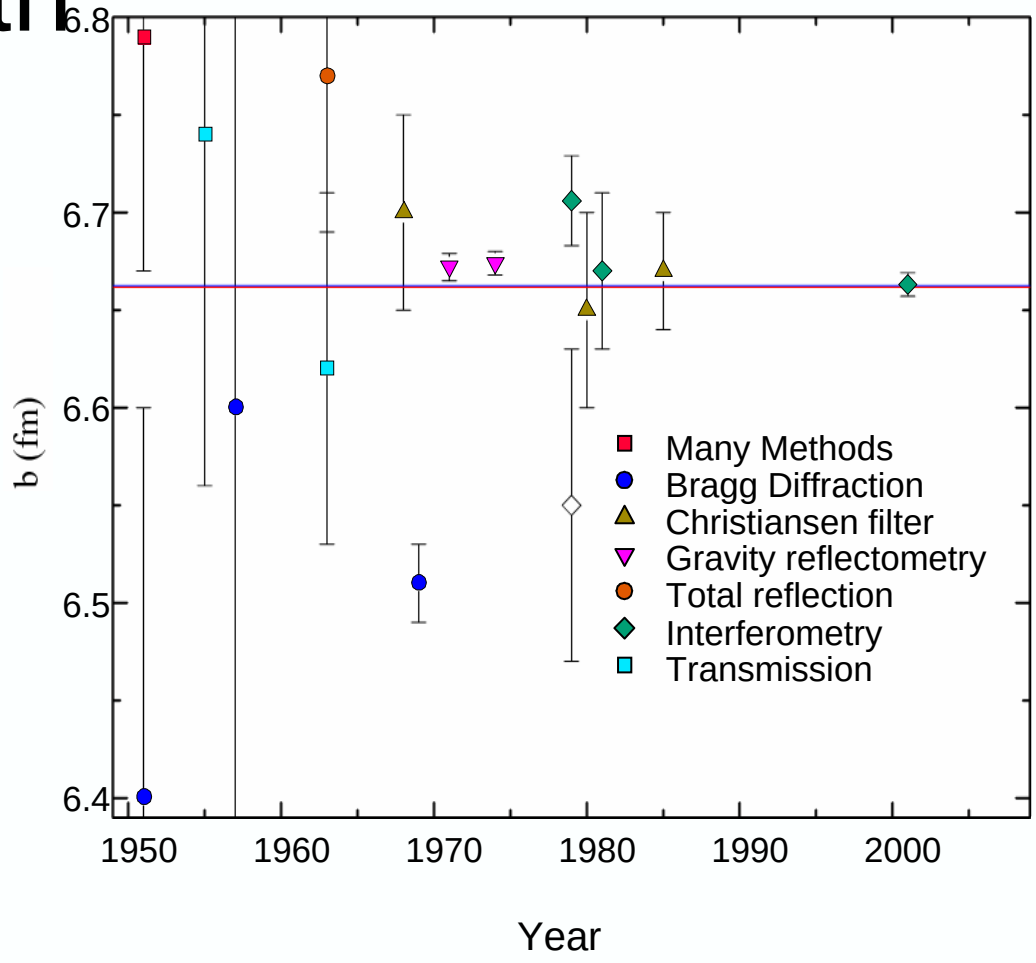
Phase shift proportional to b_{coh}

D_2 scattering length measurement

b_{nd} = (6.6727 ± 0.0045) fm



Theoretical calculations of the coherent scattering length compared with the experimental value. The central dark band is the 1σ confidence band and the lighter band is the 2σ confidence band. Only 2 of the theories fall within 2σ.



Precision measurements in 3-body systems can see effects of nuclear 3-body forces. No one knows what the nuclear 3-body force should look like.

Measurement of the *n*-^{3}He coherent scattering length

Parameter	Value *V*	Relative $\sigma V / V$
$\Delta\phi_{nD}$	2.69 rad	6.6×10^{-4}
$\Delta\phi_{cell}$	-1.379 rad	1.45×10^{-3}
λ	0.271207 nm	2.0×10^{-5}
D_{cell}	1.0016 cm	1.0×10^{-4}
T	23.237 °C	2.3×10^{-4}
P	3.380×10^5 Pa	1.0×10^{-4}
N	8.250×10^{19} cm^{-3}	3.5×10^{-4}

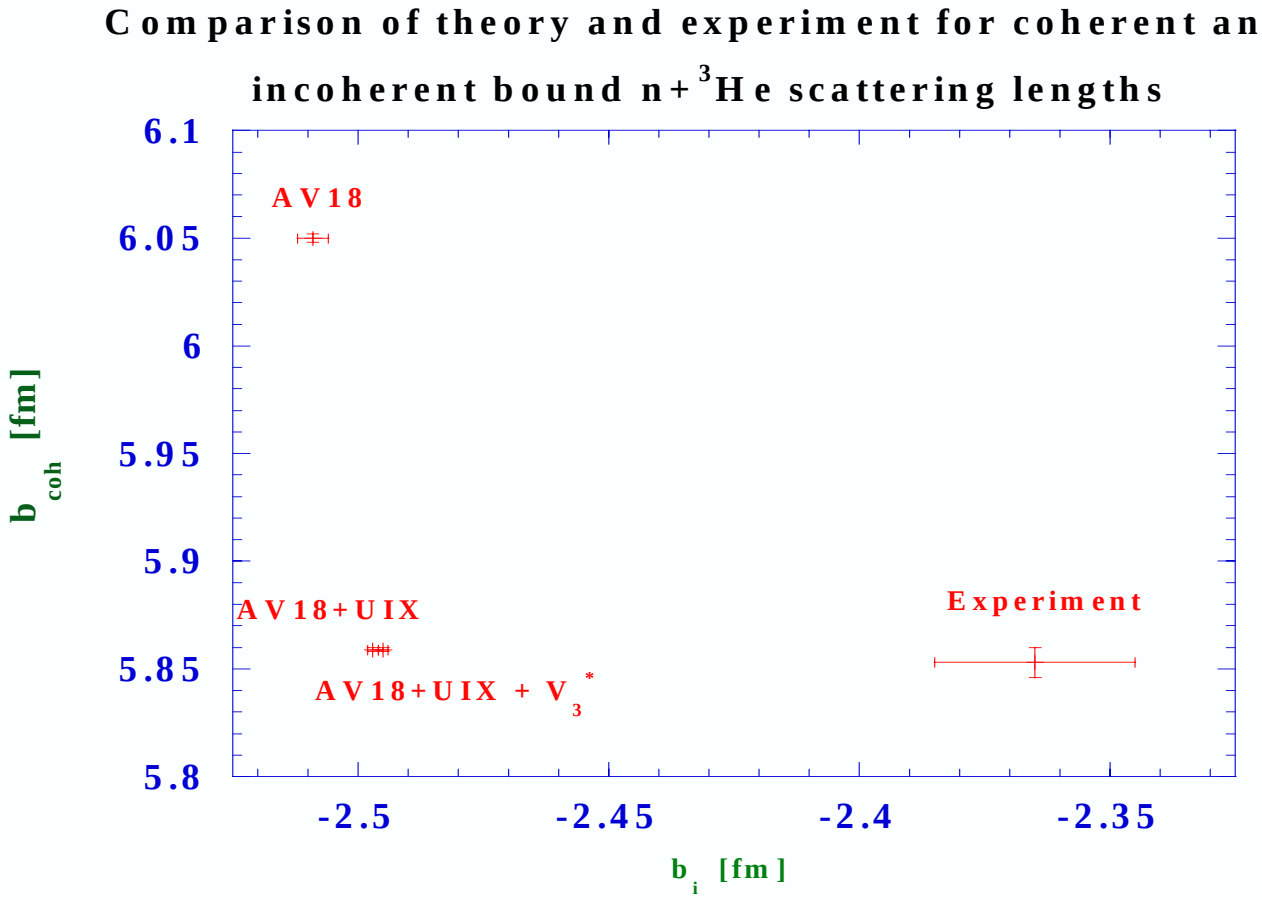
new measurement $b_{n^3He} = (5.857 \pm 0.007)$ fm

previous world average $b_{n^3He} = (5.733 \pm 0.041)$ fm

new world average $b_{n^3He} = (5.854 \pm 0.007)$ fm

•P. R. Huffman, D. L. Jacobson, K. Schoen, M. Arif, T. C. Black, W. M. Snow, and S. A. Werner, *A precision neutron interferometric measurement of the n-^{3}He coherent neutron scattering length* submitted to **Phys. Rev. C.**

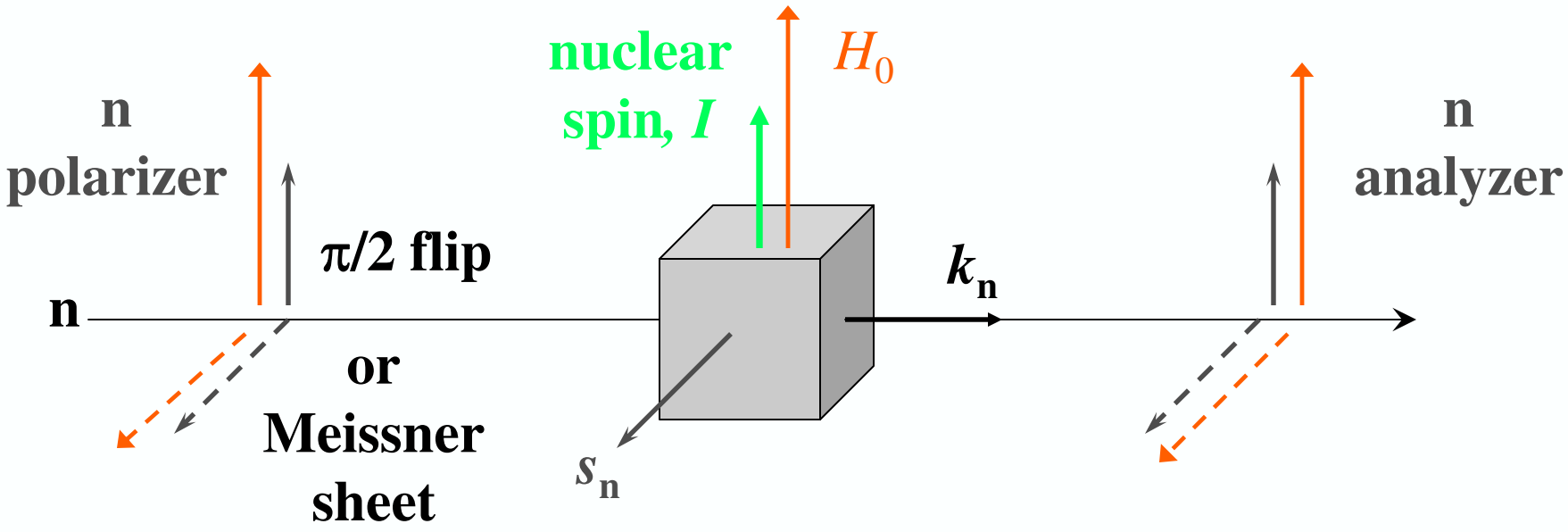
Comparisons with RGM calculations using modern NN potentials with 3N Forces*



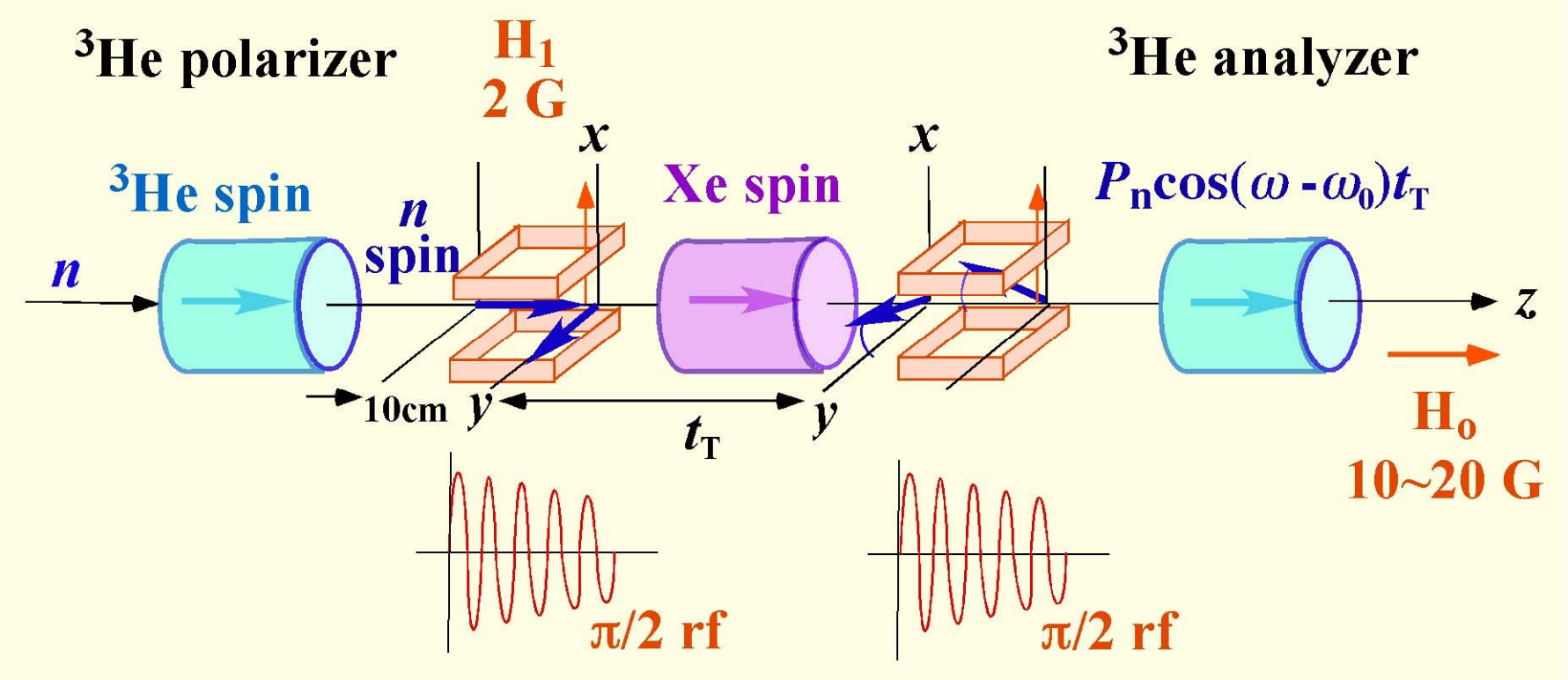
*H. M. Hoffman and G. M. Hale, **Phys. Rev. C 68**, 021002(R) (2003).

T-violation experiments in Polarized Neutron Transmission through Polarized Targets

T-odd correlation in total cross section: $(k_n \times I) \cdot s_n$



first step for T-violation experiment **measurement of Xe pseudomagnetism**



Two-particle vs. two-space entanglemen

2-Particle Bell-State

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\{|\uparrow\rangle_{\mathrm{I}} \otimes |\downarrow\rangle_{\mathrm{II}} + |\downarrow\rangle_{\mathrm{I}} \otimes |\uparrow\rangle_{\mathrm{II}}\}$$

I, II represent 2-Particles

Measurement on each particle

$$\begin{cases} \hat{\mathrm{A}}^{\mathrm{I}}(\vec{a}) = (+1)\cdot\hat{P}^{\mathrm{I}}_{(\vec{a};+1)} + (-1)\cdot\hat{P}^{\mathrm{I}}_{(\vec{a};-1)} \\ \hat{\mathrm{B}}^{\mathrm{II}}(\vec{b}) = (+1)\cdot\hat{P}^{\mathrm{II}}_{(\vec{b};+1)} + (-1)\cdot\hat{P}^{\mathrm{II}}_{(\vec{b};-1)} \end{cases}$$

where $\hat{P}_{(\vec{\xi};\pm 1)} = \frac{1}{2}(|\uparrow\rangle \pm e^{i\xi}|\downarrow\rangle)(\langle\uparrow| \pm e^{-i\xi}\langle\downarrow|)$

Then, $\left[\hat{\mathrm{A}}^{\mathrm{I}}, \hat{\mathrm{B}}^{\mathrm{II}}\right] = 0$

2-Space Bell-State

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\{|\uparrow\rangle_{\mathrm{s}} \otimes |\mathrm{I}\rangle_{\mathrm{p}} + |\downarrow\rangle_{\mathrm{s}} \otimes |\mathrm{II}\rangle_{\mathrm{p}}\}$$

s, p represent 2-Spaces, e.g., spin

Measurement on each property

$$\begin{cases} \hat{\mathrm{A}}^{\mathrm{s}}(\alpha) = (+1)\cdot\hat{P}^{\mathrm{s}}_{(\alpha)} + (-1)\cdot\hat{P}^{\mathrm{s}}_{(\alpha+\pi)} \\ \hat{\mathrm{B}}^{\mathrm{p}}(\chi) = (+1)\cdot\hat{P}^{\mathrm{p}}_{(\chi)} + (-1)\cdot\hat{P}^{\mathrm{p}}_{(\chi+\pi)} \end{cases}$$

where $\hat{P}_{(\phi)} = \frac{1}{2}(|\varphi\rangle + e^{i\phi}|\bar{\varphi}\rangle)(\langle\varphi| + e^{-i\phi}\langle\bar{\varphi}|)$

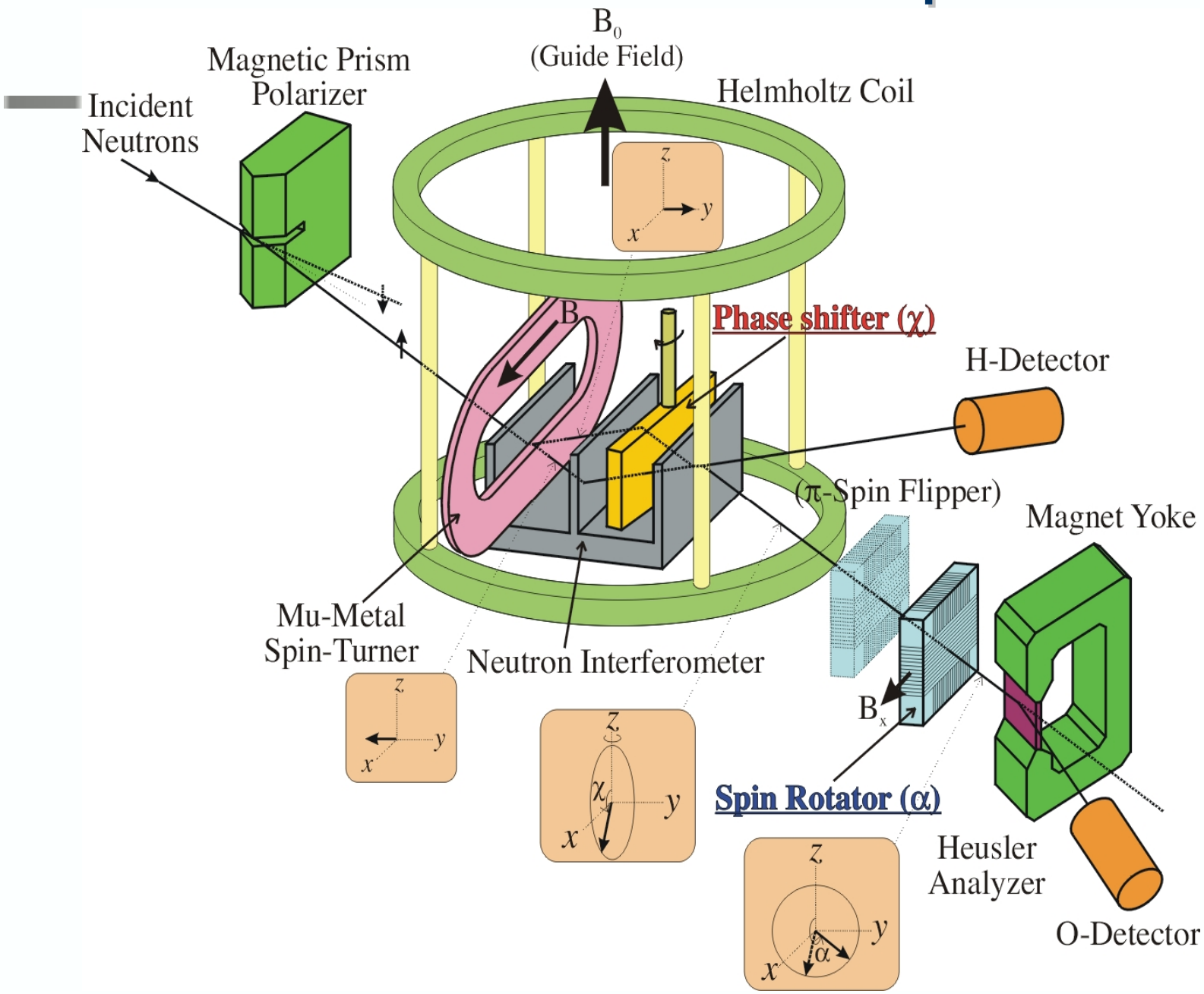
Then, $\left[\hat{\mathrm{A}}^{\mathrm{s}}, \hat{\mathrm{B}}^{\mathrm{p}}\right] = 0$

==>> (Non-)Contextuality

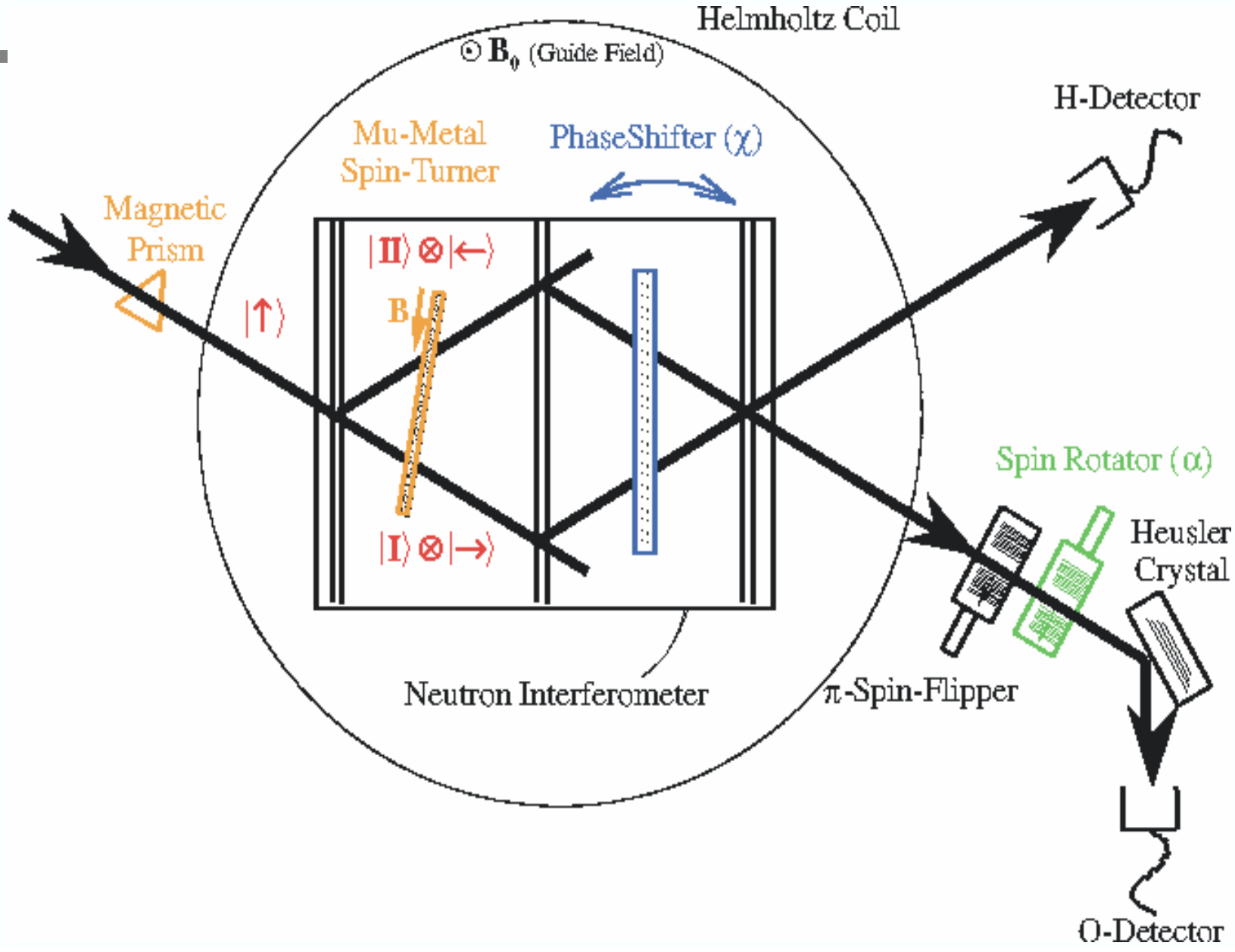
(In)Dependent Results for commuting Observables

Non-Locality: $\mathbf{r}_{\mathrm{I}} \neq \mathbf{r}_{\mathrm{II}}$ for $\hat{P}^{\mathrm{I}(\mathbf{r}_{\mathrm{I}})}$ & $\hat{P}^{\mathrm{II}(\mathbf{r}_{\mathrm{II}})}$

Schematic view of the experiment

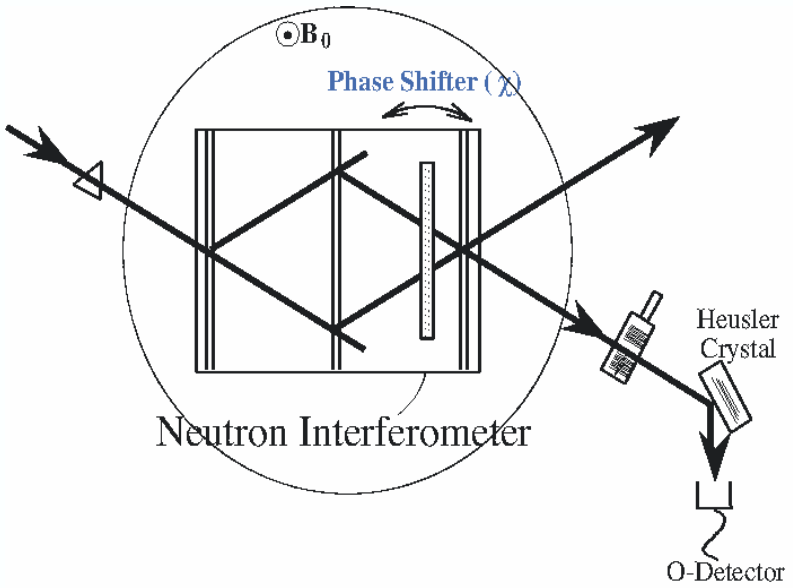


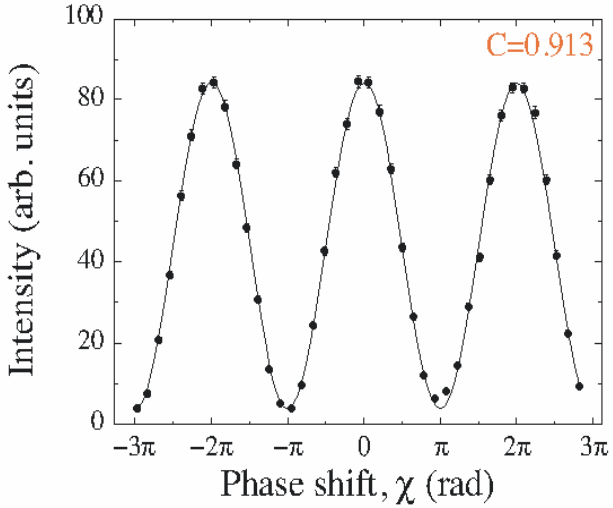
Top View


Helmholtz Coil
$\odot B_0$ (Guide Field)
H-Detector
Mu-Metal
Spin-Turner
PhaseShifter (χ)
Magnetic
Prism
$|\uparrow\rangle$
$|\mathrm{II}\rangle \otimes |\leftarrow\rangle$
B
$|\mathrm{I}\rangle \otimes |\rightarrow\rangle$
Spin Rotator (α)
Heusler
Crystal
Neutron Interferometer
π-Spin-Flipper
O-Detector

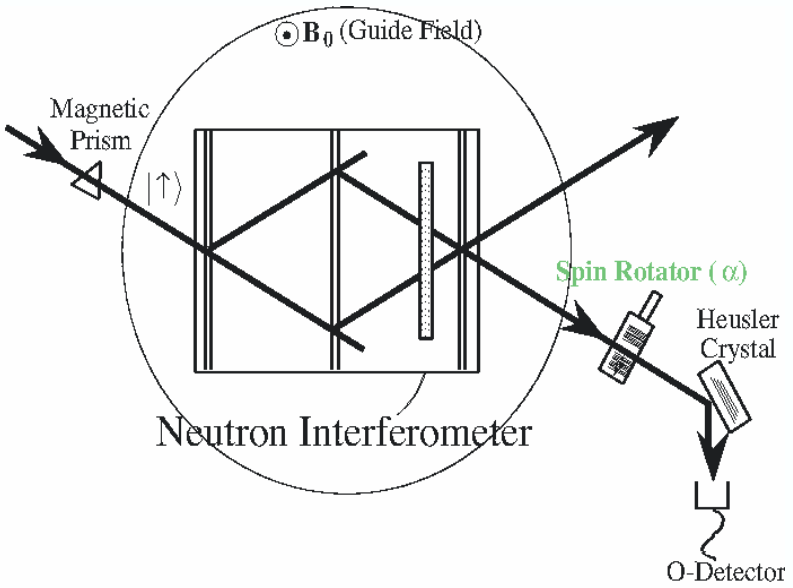
Manipulation of two-subspaces

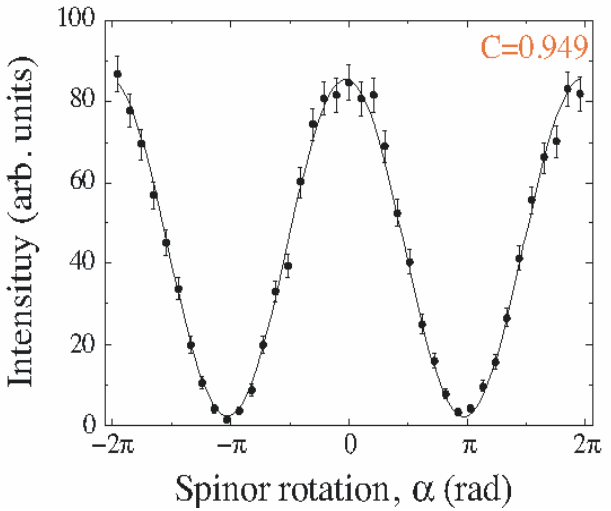
(a) Path



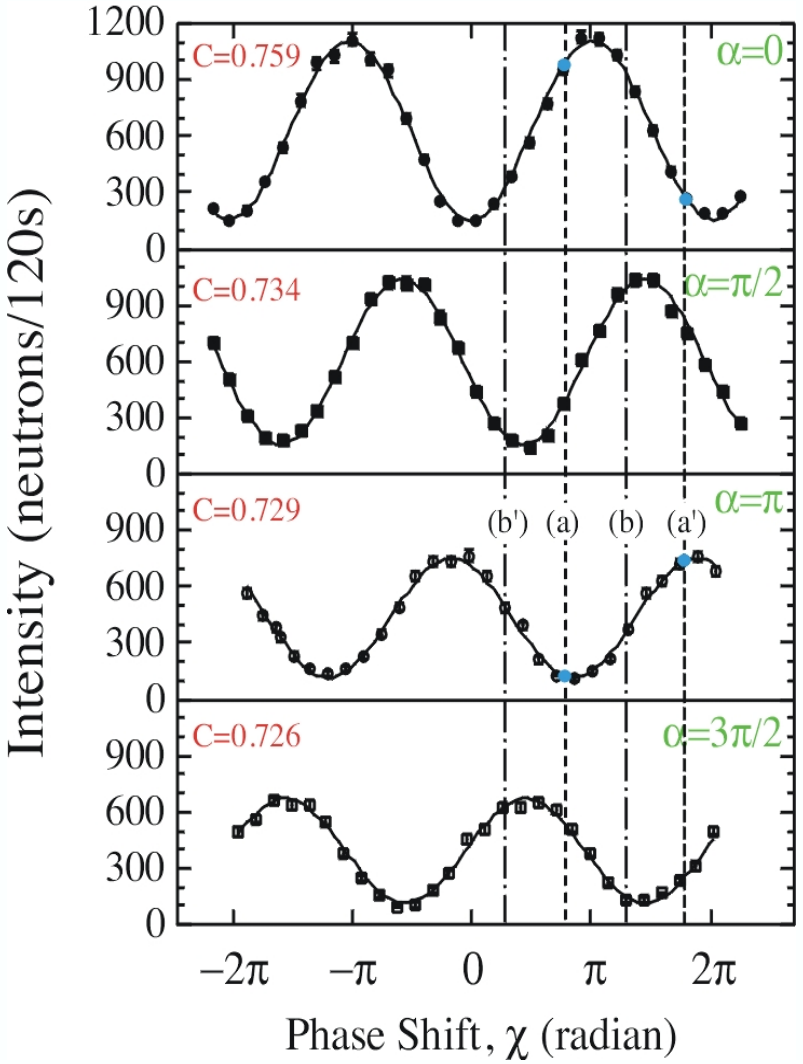


(b) Spin





Oscillations with various spin-analyses



$$
\begin{aligned}
&E'(\alpha=0, \chi = 0.79\pi) \\
= &\left[N'(0,0.79\pi) + N'(\pi,1.79\pi)\right. \\
&\left. - N'(0,1.79\pi) - N'(\pi,0.79\pi)\right] \\
\div &\left[N'(0,0.79\pi) + N'(\pi,1.79\pi)\right. \\
&\left. + N'(0,1.79\pi) + N'(\pi,0.79\pi)\right] \\
= &\, 0.542
\end{aligned}
$$

In the same manner,

$$
\begin{cases}
E'(\alpha=0, \chi = 1.29\pi) \\
E'(\alpha=0.5\pi, \chi = 0.79\pi) \\
E'(\alpha=0.5\pi, \chi = 1.29\pi)
\end{cases}
$$

were determined

Violation of the Bell-like inequality

$$E'(\alpha,\chi) = \frac{N'_{++}(\alpha,\chi) + N'_{++}(\alpha+\pi,\chi+\pi) - N'_{++}(\alpha,\chi+\pi) - N'_{++}(\alpha+\pi,\chi)}{N'_{++}(\alpha,\chi) + N'_{++}(\alpha+\pi,\chi+\pi) + N'_{++}(\alpha,\chi+\pi) + N'_{++}(\alpha+\pi,\chi)}$$

where $N'_{++}(\alpha,\chi) = \langle \Psi | \hat{P}^{s}_{(\alpha)} \cdot \hat{P}^{p}_{(\chi)} | \Psi \rangle$

$$\begin{cases} E'(\alpha_1,\chi_1) = \quad 0.542 \pm 0.007 \\ E'(\alpha_1,\chi_2) = \quad 0.488 \pm 0.012 \\ E'(\alpha_2,\chi_1) = -0.538 \pm 0.006 \\ E'(\alpha_2,\chi_2) = \quad 0.483 \pm 0.012 \end{cases} \qquad \text{where} \begin{cases} \alpha_1 = 0 \\ \alpha_2 = 0.50\pi \\ \chi_1 = 0.79\pi \\ \chi_2 = 1.29\pi \end{cases}$$

$$===>>> \quad S' \equiv E'(\alpha_1,\chi_1) + E'(\alpha_1,\chi_2) - E'(\alpha_2,\chi_1) + E'(\alpha_2,\chi_2)$$

$$= \mathbf{2.051 \pm 0.019 > 2}$$

confidence: 99.6%

Cf. Max. violaion: S'=2.81>2