Searches for Exotic Neutron Interactions with Neutron Interferometric Measurements

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Advantages of “very cold” neutrons for this work

Example scientific activities happening today:
1. Searches for exotic neutron spin/electron spin interactions
2. Neutron mode entanglement
3. Neutron Sagnac effect
4. Neutron searches for exotic short-range gravity
5. Neutron storage ring?

Thanks for slides to: Hiro Shimizu, K. Lopez, T. Mulkey, A. Young, K. Leung, M. Huber, V. Nesvizhevsky, H. Abele, S. Parnell, F. Li, …

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NSF PHY-2209481

Useful Features of Slow Neutrons

1. Zero electric charge, small magnetic moment, very small electric polarizability->low ”background” from Standard Model interactions

2. Deep penetration distance through macroscopic amounts of condensed matter

3. Coherent interactions with matter->phase sensitive measurements possible inside matter

4. High neutron polarization (>~99%) routine for slow neutrons
->important in searching for spin-dependent interactions

4. A broad set of facilities for experimental work is available

J. Nico and W. M. Snow, Annual Reviews of Nuclear and Particle Science **55**, 27-69 (2005).
H. Abele, Progress in Particle and Nuclear Physics **60**, 1-81 (2008).
D. Dubbers and M. Schmidt, Reviews of Modern Physics (2011).

Why can VCN neutrons be interesting?

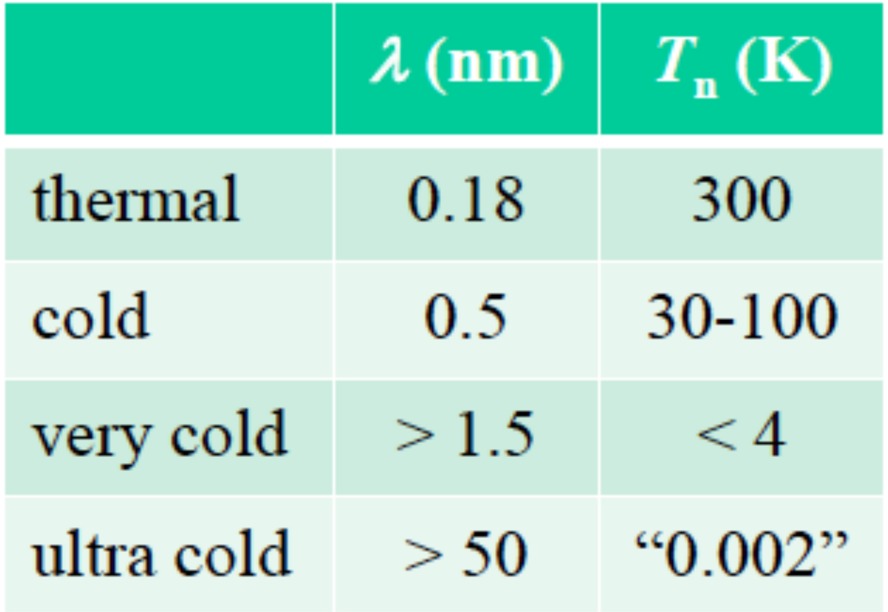
All else being equal, slower neutron beams:

Are more easily manipulated by coherent external fields (optical potentials, B, gravity) which (can) preserve polarization

Can be turned into interferometers more easily

Can be detected and imaged with higher spatial precision (neutron absorption cross sections grow with λ)

What are “very-cold neutrons”?



	λ (nm)	T_n (K)
thermal	0.18	300
cold	0.5	30-100
very cold	> 1.5	< 4
ultra cold	> 50	“0.002”

Neutron optics is easier for colder neutrons

$$n = \sqrt{1 - \frac{V_0}{E_n}}$$

$<V_{strong}>=2\pi h^2 \rho b_s/m$, ~+/- 100 neV
$<V_{mag}>=\mu B$, ~+/- 60 neV/Tesla
$<V_{grav}>=mgz$~100 neV/m

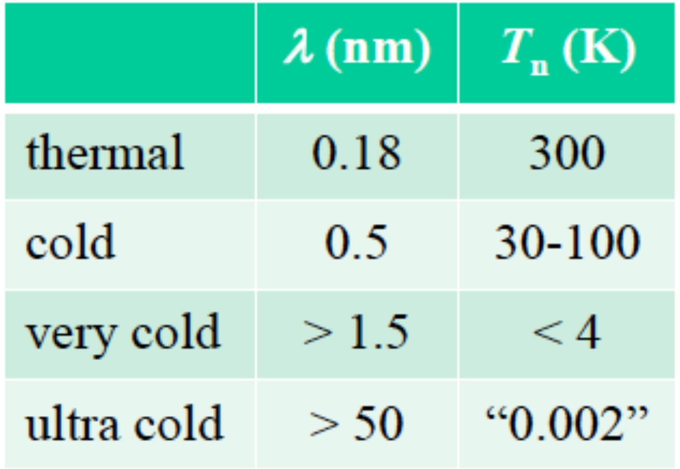
Neutron optics is easier the more n differs from 1: $n-1 \approx \lambda^2$

Hard to increase V_0: more improvement possible by lowering E_n

Neutron focusing is easier.

Slower neutrons+position sensitive detector
->gravity can give neutron energy analysis for free

σ_a increases->sharp beam definition, detector spatial resolution



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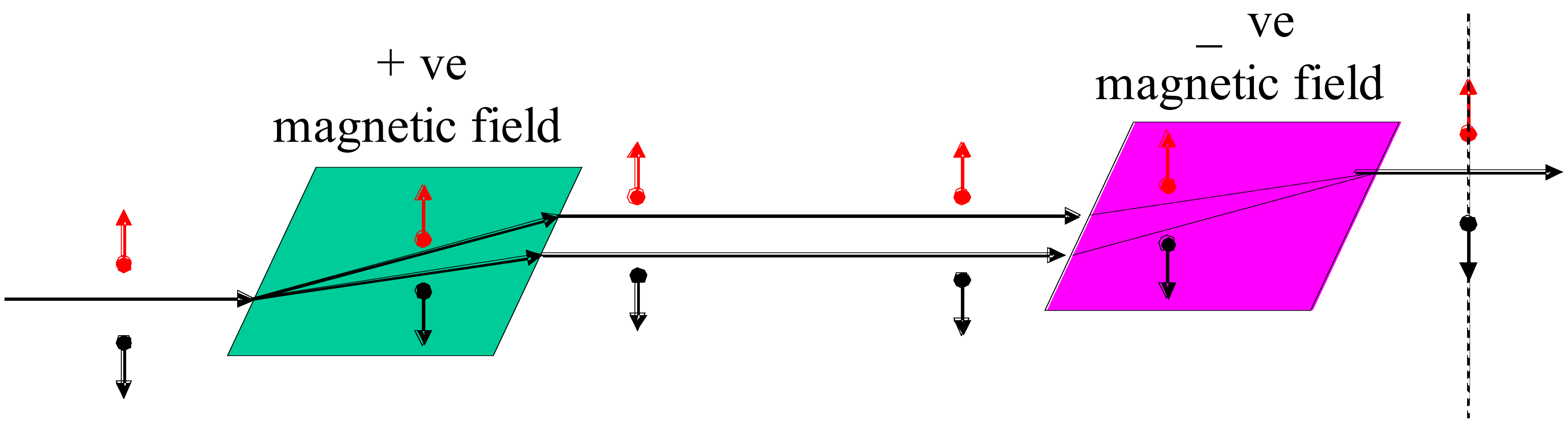
Neutron interferometry/polarization manipulation is easier for colder neutrons



EXAMPLE: neutron spin echo (SESAME pictured above):

Spatial separation of helicities of n spin state ≈ λ^2

Time separation of helicities of n spin state ≈ λ^3

Neutron spin echo spectrometers are interferometers using B fields to split and recombine neutron spin states in space and time. Pulsed source sweeps through broad dynamic range of neutron energy

	λ (nm)	T_n (K)
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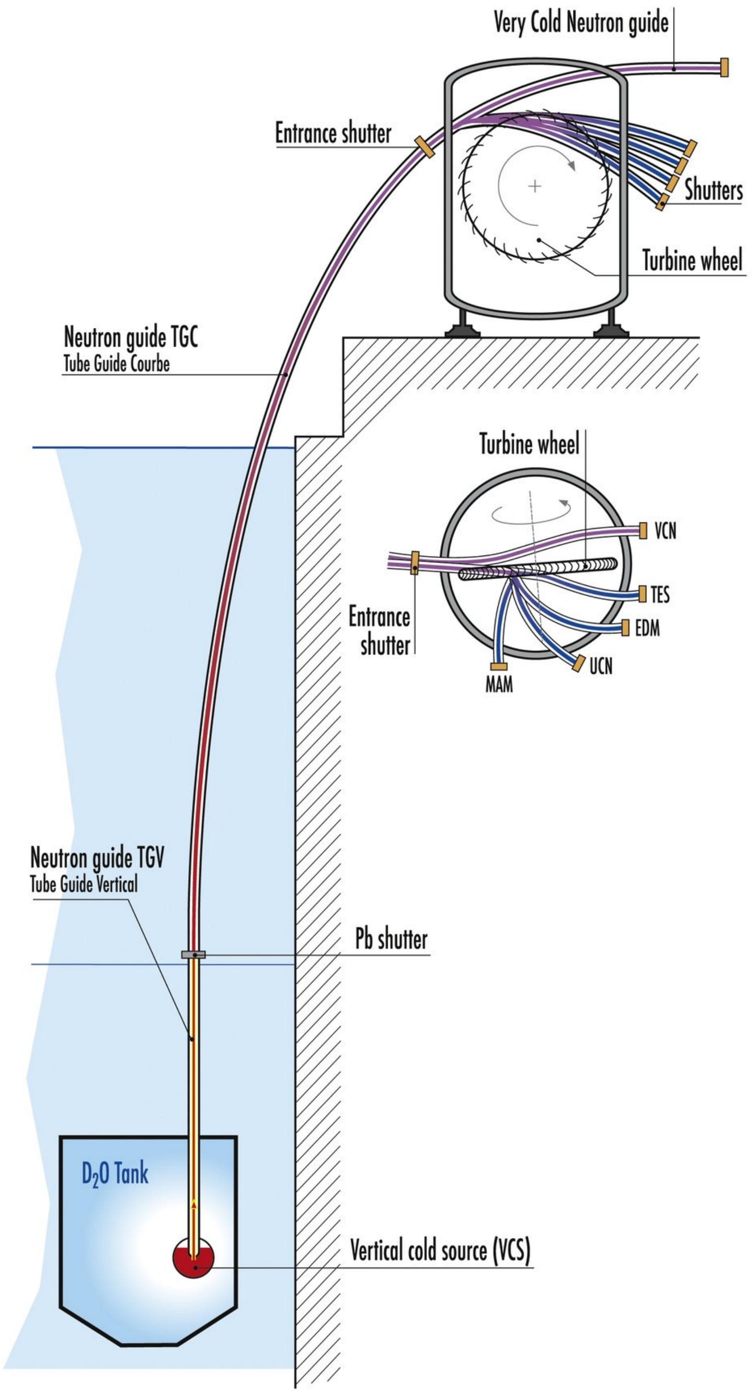
ILL VCN facility



Only VCN neutron beam user facility in the world

Flagship facility (K. Leung) can make X100 more VCN

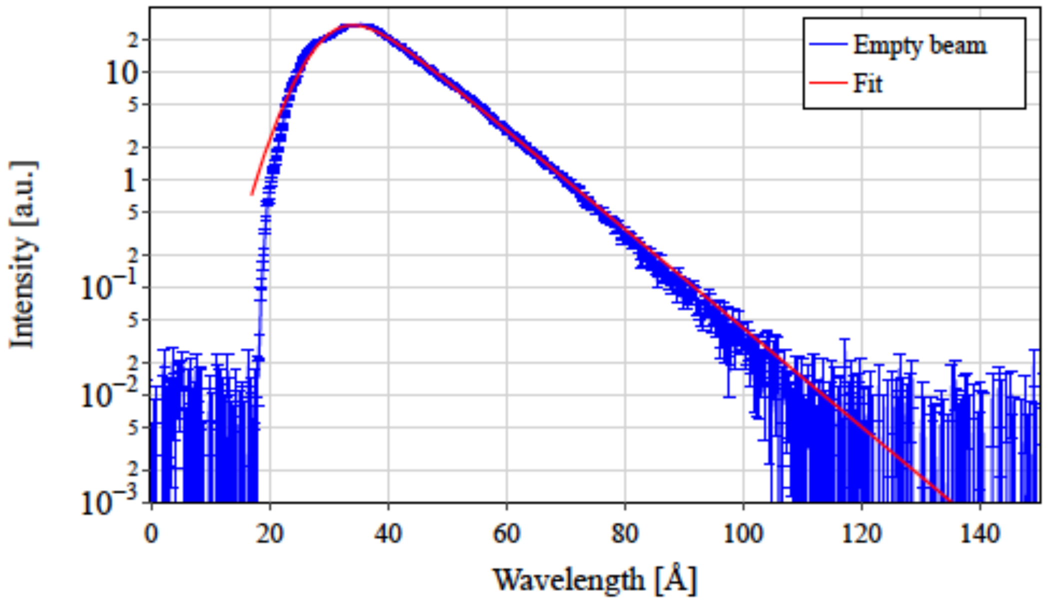
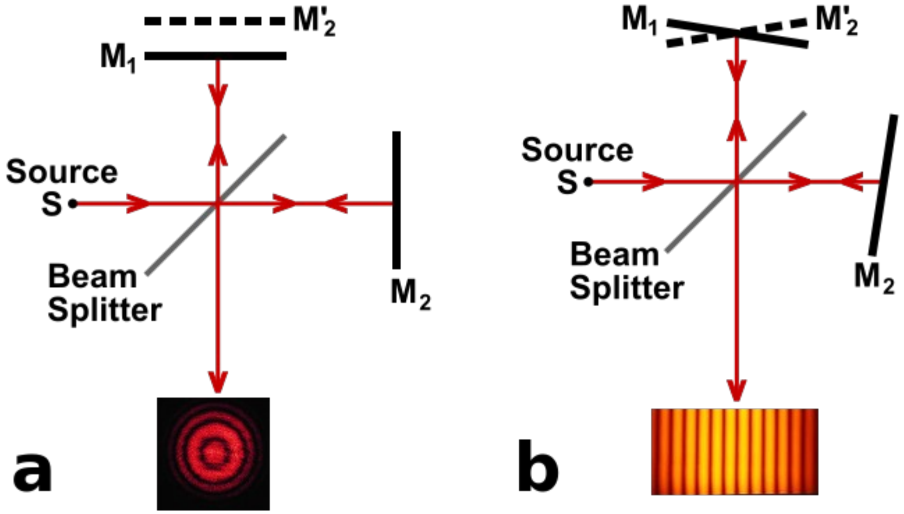


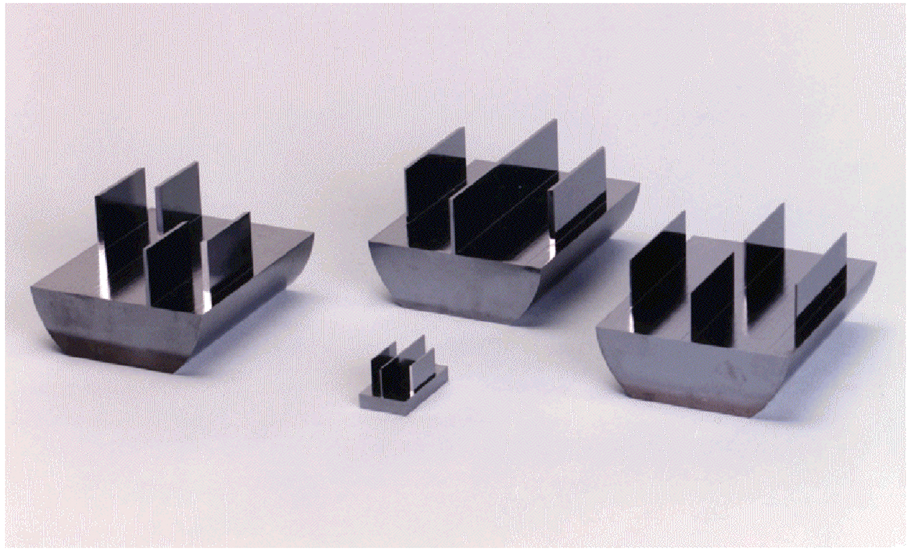
Figure 6.23.: Selected wavelength spectrum of the PF2/VCN beamline measured with setup described above. The spectrum has a maximum at roughly 36 Å. The fit function is given in equation 6.29 with the parameters of Table 6.9.

V. Czamler, Deuterated Clathrate Hydrates as novel Moderator Material for a Source of Very Cold Neutrons, PhD thesis, University of Grenoble (2024)

Neutron interferometer from perfect xtal diffraction

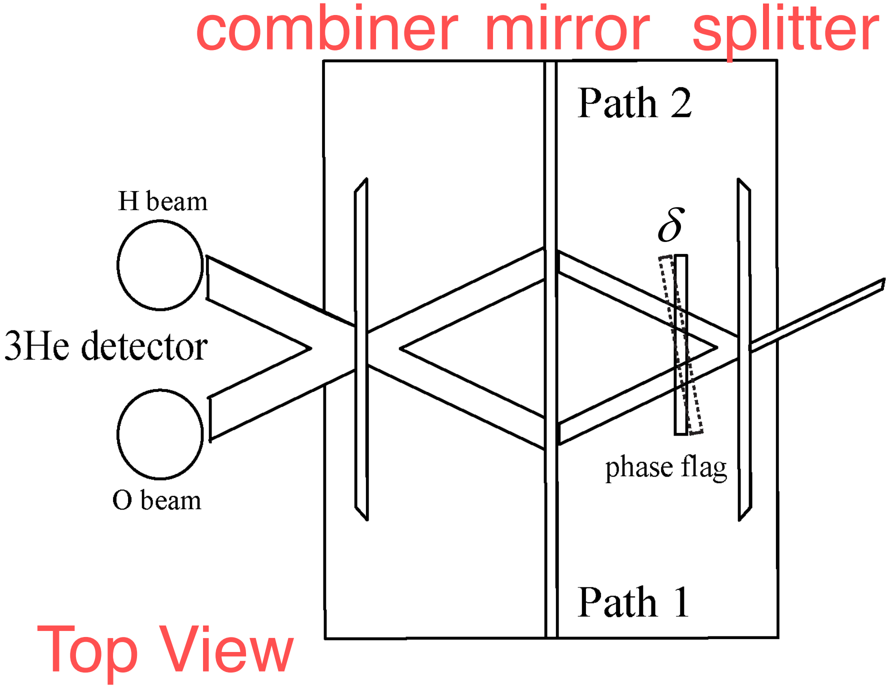
Michaelson interferometer





Neutron interferometer is very similar to a light interferometer:

1) Split
2) Diffract (rather than reflect)
3) Recombine



Neutron Optics' View

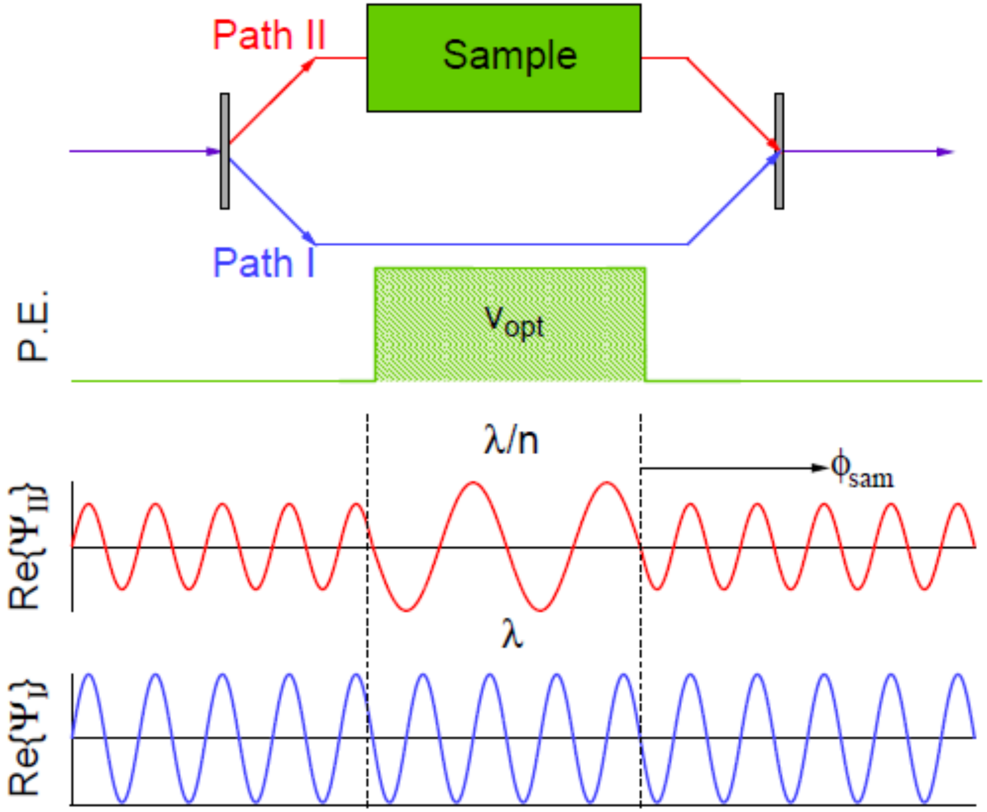
- neutron optical potential difference causes neutron phase shift.

$$\left(\frac{\hbar^2 K^2}{2m_{\mathrm{n}}} + V_{\mathrm{opt}}\right)\psi = \frac{\hbar^2 k^2}{2m_{\mathrm{n}}}\psi,$$

$$V_{\mathrm{opt}} = \frac{2\pi\hbar^2}{m_{\mathrm{n}}} Nb,$$

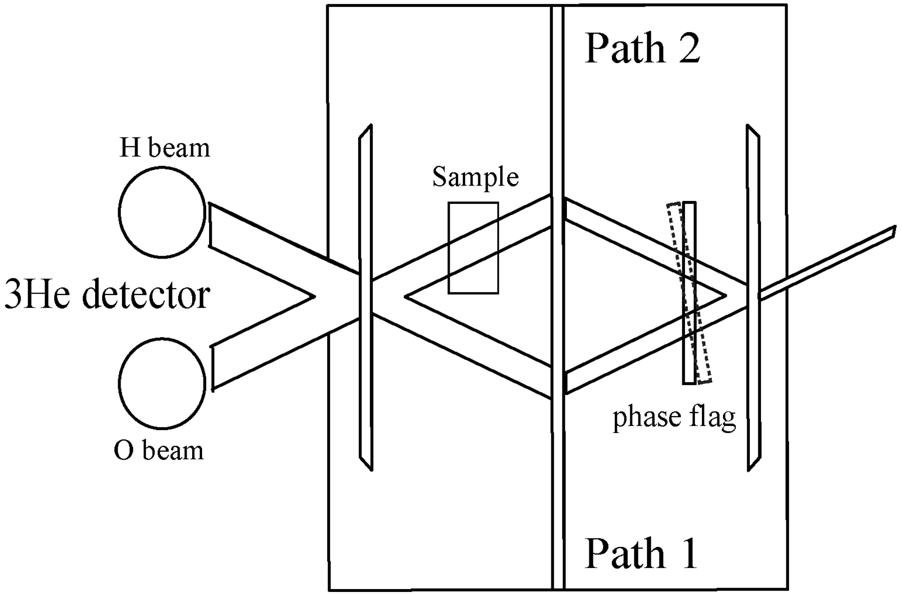
$$n = \frac{K}{k} = \sqrt{1 - \frac{\lambda^2 Nb}{\pi}},$$

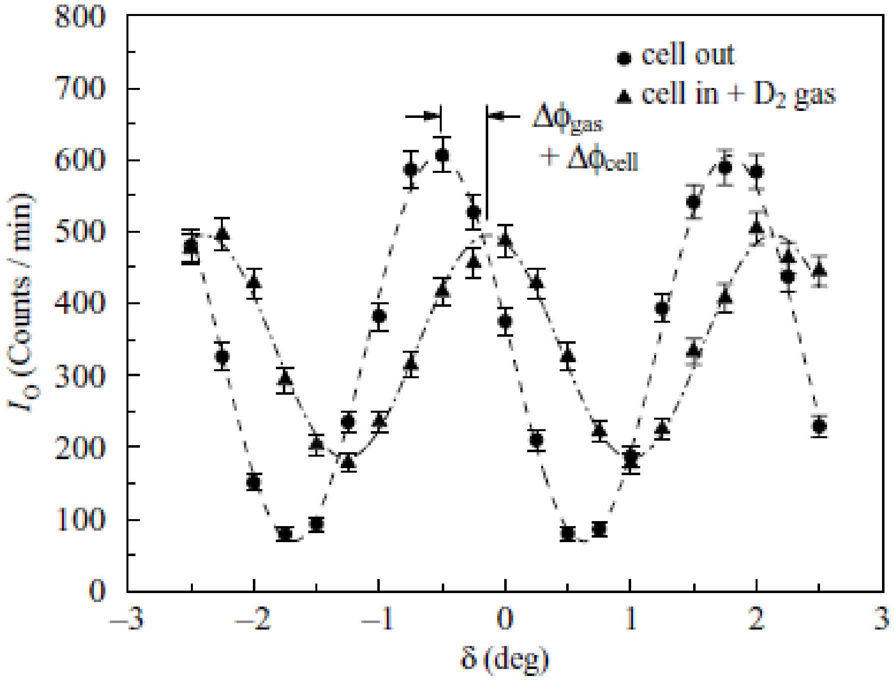
K, k: neutron wave number in material and vacuum



M. G. Huber, et al., Phys. Rev. C 90, 064004 (2014).

How it works to measure the optical potential





It measures the extra phase shift caused by sample.

From dynamic diffraction theory:

O beam: $I_0 = A(1 + f\cos(\Delta\Phi))$

H beam: $I_H = B - Af\cos(\Delta\Phi))$

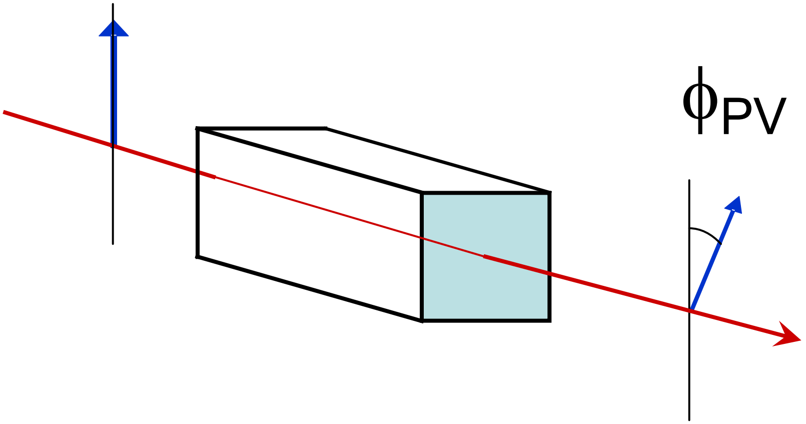
$\Delta\Phi$: phase shift between two paths

f : contrast/visibility

Precision neutron interferometric measurements and updated evaluations of the n−p and n−d coherent neutron scattering lengths, Phys. Rev. C **67**, 044005

Neutron Spin Rotation as a "Spin-Space" Interferometer (Example: parity violation)

$$\left|\uparrow\right\rangle_i = \frac{1}{\sqrt{2}}\left(\left|+\right\rangle + \left|-\right\rangle\right)$$



$$\frac{1}{\sqrt{2}}\left(e^{-i(\phi_{PC}+\phi_{PV})}\left|z\right\rangle + e^{-i(\phi_{PC}-\phi_{PV})}\left|-z\right\rangle\right)$$

- Analogous to optical activity in a "handed" medium.
- Transversely-polarized neutrons corkscrew from a P-odd neutron interaction with matter
- Same argument applies for any neutron spin-dependent interaction

Neutron refractive index dependence on neutron helicity

$$f(0) = f_{PC} + f_{PV}\left(\vec{\sigma}\cdot\vec{k}\right)$$

$$\phi_{PV} = 4\pi L\rho f_{PV}$$

New weakly-coupled, long- range interactions… “Who ordered that?”

1. Weakly-coupled, long-range interactions are a generic consequence of spontaneously broken continuous symmetries in QFT (Goldstone theorem)

2. Many theoretical ideas (axions/axion-like particles, Z` bosons, extra dimensions from string theory,…) can produce new spin-dependent ultraweak, long-range interactions

3. Mysteries of dark matter and dark energy remain

Experiments should look

J. Jaeckel and A. Ringwald, Ann. Rev. Nucl. Part. Sci. 60, 405 (2010).
Antionadis et al, Comptes Rendus Physique 12, 755-778 (2011)
M. S. Safronova et al, Rev. Mod. Phys. 97, 025008 (2018)
L. Cong et al, Rev. Mod. Phys. 97, 025005 (2025)

Exotic Neutron Spin-Dependent Interaction Searches

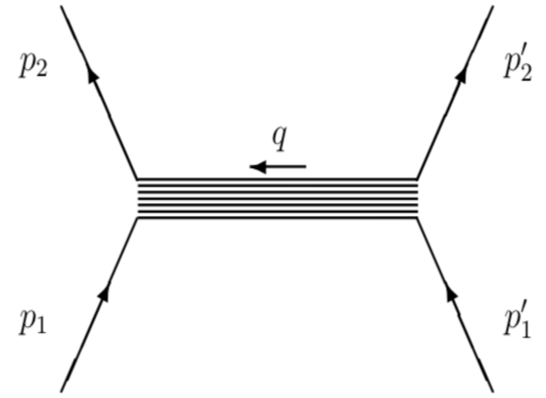


Figure 1: Elastic scattering of two fermions mediated by some very light particles represented generically by the horizontal blob of four-momentum q.

Laboratory limits are especially poor for spin-dependent interactions over distances from atomic to ~mm scales

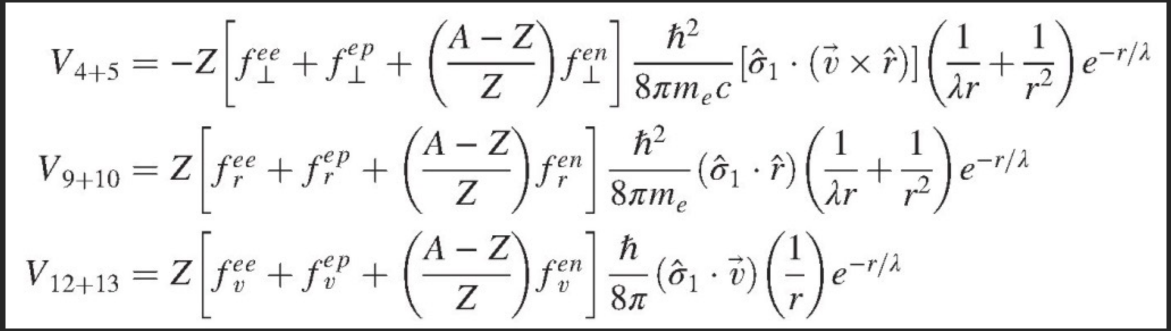
- Neutrons are uniquely well-suited to probe for interactions of this range

- Conduct sensitive searches in a regime not (yet?) accessible to other techniques

In the nonrelativistic limit, the # of possibilities is severely constrained

Example 3: Exotic Neutron spin-electron-spin

- How do you make a macroscopic polarized electron target without a huge magnetic background?

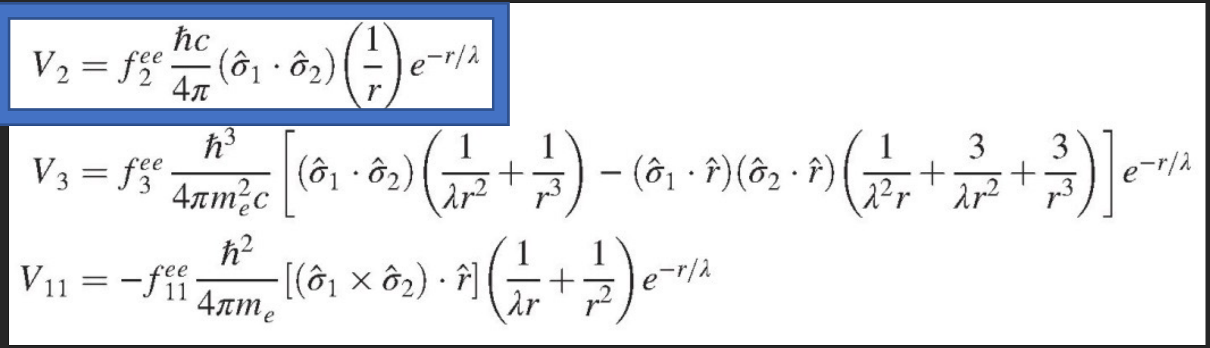


$$V_{4+5} = -Z\left[f_{\perp}^{ee} + f_{\perp}^{ep} + \left(\frac{A-Z}{Z}\right)f_{\perp}^{en}\right]\frac{\hbar^2}{8\pi m_e c}[\hat{\sigma}_1 \cdot (\vec{v} \times \hat{r})]\left(\frac{1}{\lambda r} + \frac{1}{r^2}\right)e^{-r/\lambda}$$

$$V_{9+10} = Z\left[f_{r}^{ee} + f_{r}^{ep} + \left(\frac{A-Z}{Z}\right)f_{r}^{en}\right]\frac{\hbar^2}{8\pi m_e}(\hat{\sigma}_1 \cdot \hat{r})\left(\frac{1}{\lambda r} + \frac{1}{r^2}\right)e^{-r/\lambda}$$

$$V_{12+13} = Z\left[f_{v}^{ee} + f_{v}^{ep} + \left(\frac{A-Z}{Z}\right)f_{v}^{en}\right]\frac{\hbar}{8\pi}(\hat{\sigma}_1 \cdot \vec{v})\left(\frac{1}{r}\right)e^{-r/\lambda}$$

Single Spin interactions

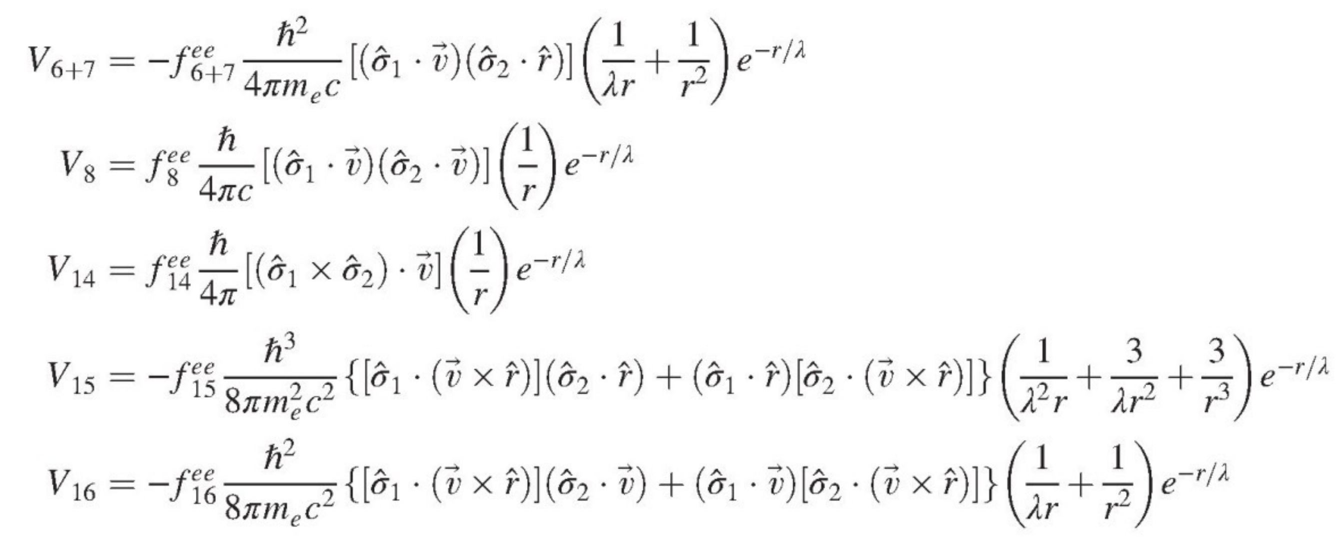


$$\boxed{V_2 = f_2^{ee}\frac{\hbar c}{4\pi}(\hat{\sigma}_1 \cdot \hat{\sigma}_2)\left(\frac{1}{r}\right)e^{-r/\lambda}}$$

$$V_3 = f_3^{ee}\frac{\hbar^3}{4\pi m_e^2 c}\left[(\hat{\sigma}_1 \cdot \hat{\sigma}_2)\left(\frac{1}{\lambda r^2} + \frac{1}{r^3}\right) - (\hat{\sigma}_1 \cdot \hat{r})(\hat{\sigma}_2 \cdot \hat{r})\left(\frac{1}{\lambda^2 r} + \frac{3}{\lambda r^2} + \frac{3}{r^3}\right)\right]e^{-r/\lambda}$$

$$V_{11} = -f_{11}^{ee}\frac{\hbar^2}{4\pi m_e}[(\hat{\sigma}_1 \times \hat{\sigma}_2) \cdot \hat{r}]\left(\frac{1}{\lambda r} + \frac{1}{r^2}\right)e^{-r/\lambda}$$

"Static" spin-spin interactions



$$V_{6+7} = -f_{6+7}^{ee}\frac{\hbar^2}{4\pi m_e c}[(\hat{\sigma}_1 \cdot \vec{v})(\hat{\sigma}_2 \cdot \hat{r})]\left(\frac{1}{\lambda r} + \frac{1}{r^2}\right)e^{-r/\lambda}$$

$$V_8 = f_8^{ee}\frac{\hbar}{4\pi c}[(\hat{\sigma}_1 \cdot \vec{v})(\hat{\sigma}_2 \cdot \vec{v})]\left(\frac{1}{r}\right)e^{-r/\lambda}$$

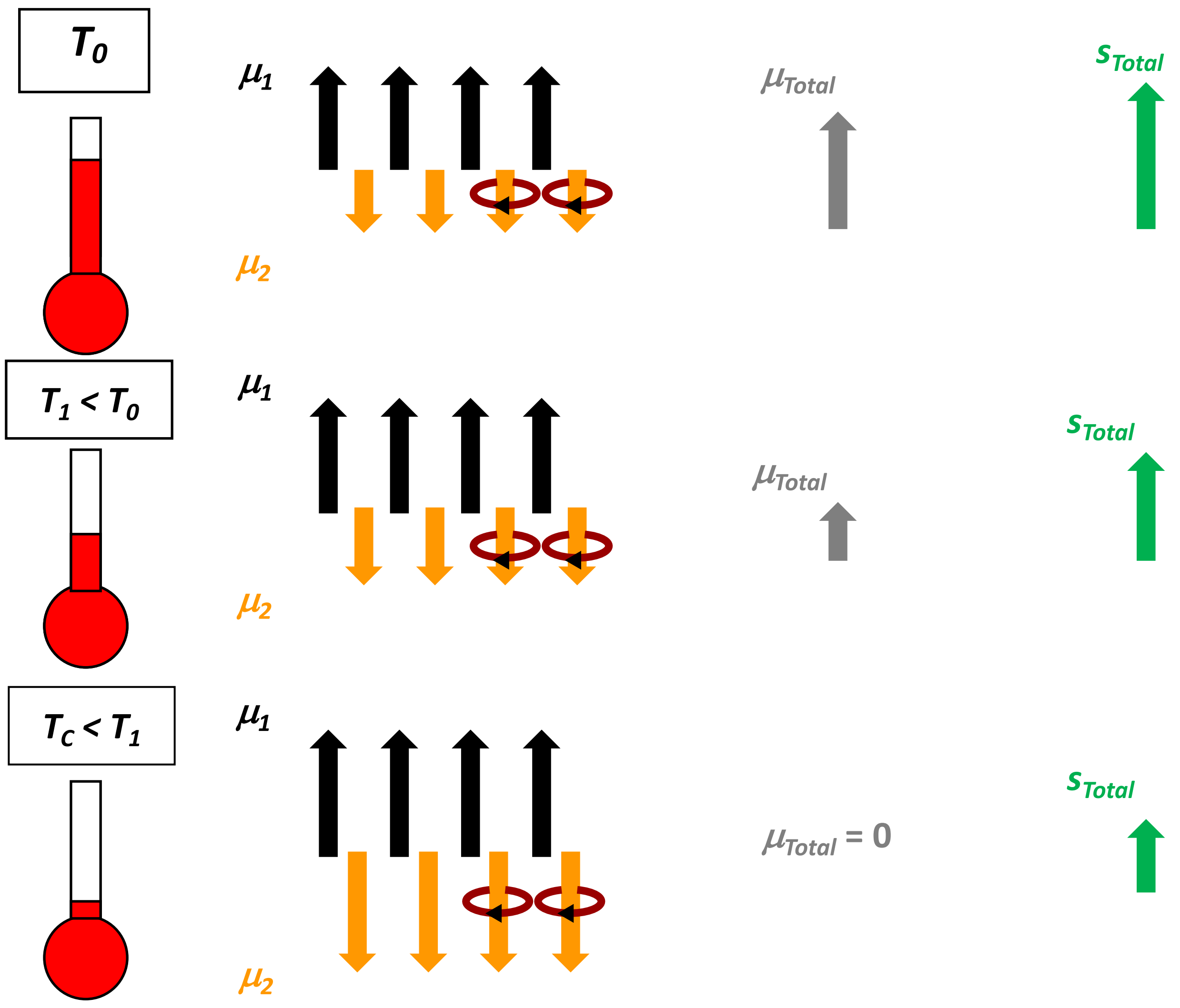
$$V_{14} = f_{14}^{ee}\frac{\hbar}{4\pi}[(\hat{\sigma}_1 \times \hat{\sigma}_2) \cdot \vec{v}]\left(\frac{1}{r}\right)e^{-r/\lambda}$$

$$V_{15} = -f_{15}^{ee}\frac{\hbar^3}{8\pi m_e^2 c^2}\{[\hat{\sigma}_1 \cdot (\vec{v} \times \hat{r})](\hat{\sigma}_2 \cdot \hat{r}) + (\hat{\sigma}_1 \cdot \hat{r})[\hat{\sigma}_2 \cdot (\vec{v} \times \hat{r})]\}\left(\frac{1}{\lambda^2 r} + \frac{3}{\lambda r^2} + \frac{3}{r^3}\right)e^{-r/\lambda}$$

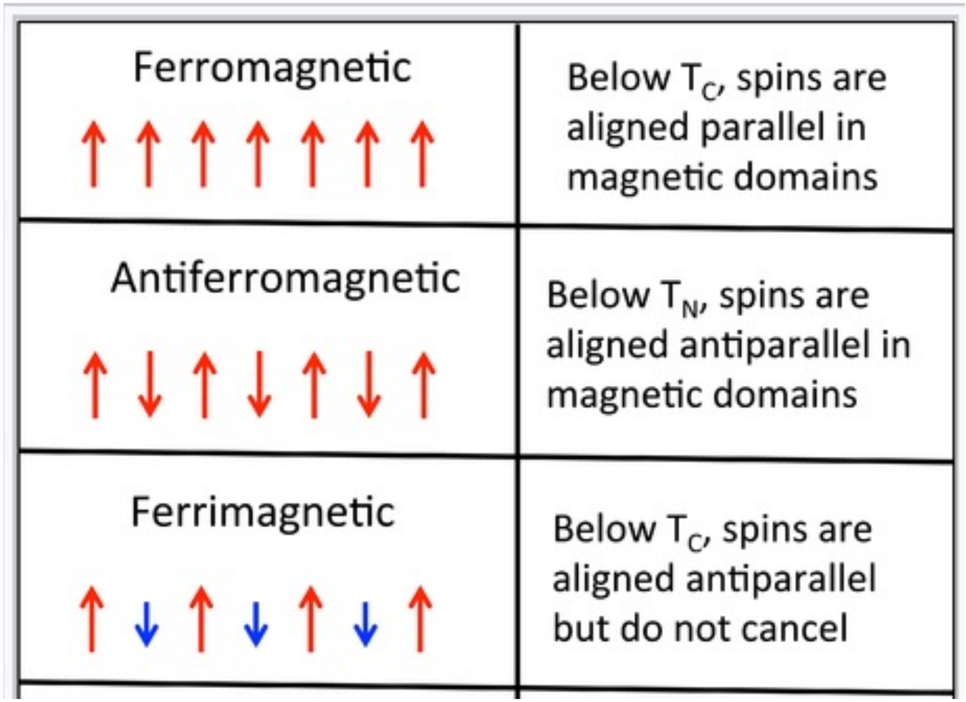
$$V_{16} = -f_{16}^{ee}\frac{\hbar^2}{8\pi m_e c^2}\{[\hat{\sigma}_1 \cdot (\vec{v} \times \hat{r})](\hat{\sigma}_2 \cdot \vec{v}) + (\hat{\sigma}_1 \cdot \vec{v})[\hat{\sigma}_2 \cdot (\vec{v} \times \hat{r})]\}\left(\frac{1}{\lambda r} + \frac{1}{r^2}\right)e^{-r/\lambda}$$

Velocity-dependent spin-spin interactions

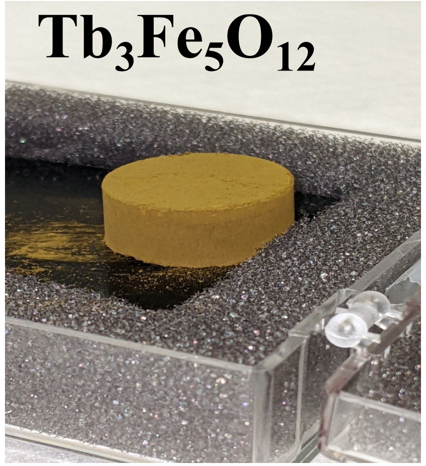
Rare Earth iron Garnets and Ferrimagnetism

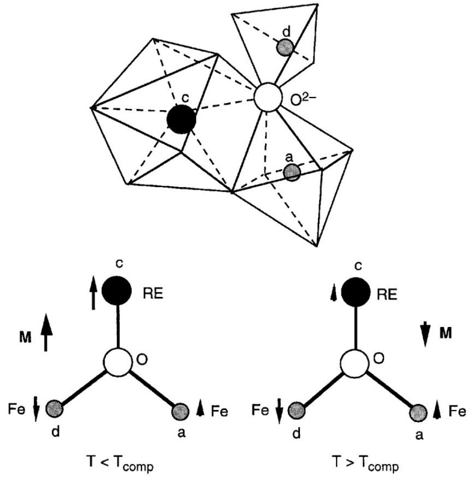


$$T_C \approx 250.60\ K$$



Ferromagnetic ↑ ↑ ↑ ↑ ↑ ↑ ↑	Below T_C, spins are aligned parallel in magnetic domains
Antiferromagnetic ↑ ↓ ↑ ↓ ↑ ↓ ↑	Below T_N, spins are aligned antiparallel in magnetic domains
Ferrimagnetic ↑ ↓ ↑ ↓ ↑ ↓ ↑	Below T_C, spins are aligned antiparallel but do not cancel

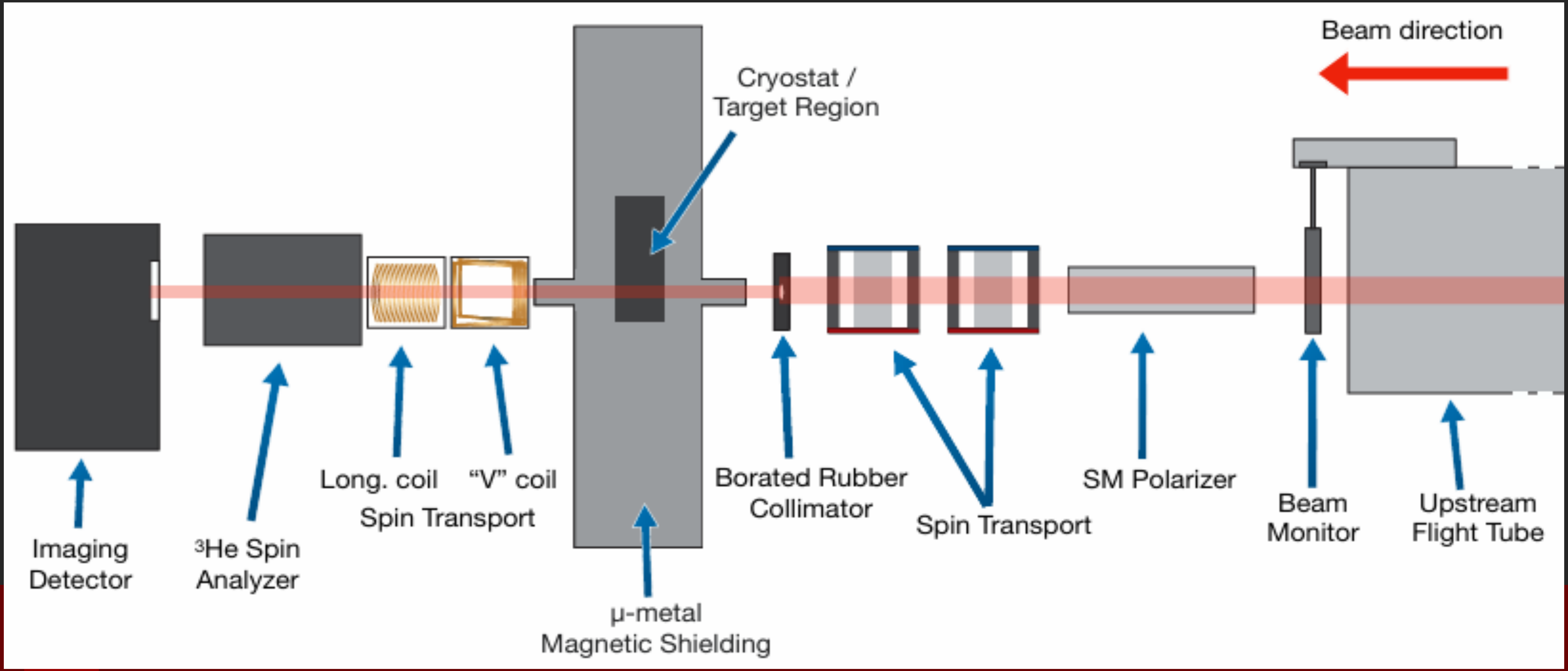


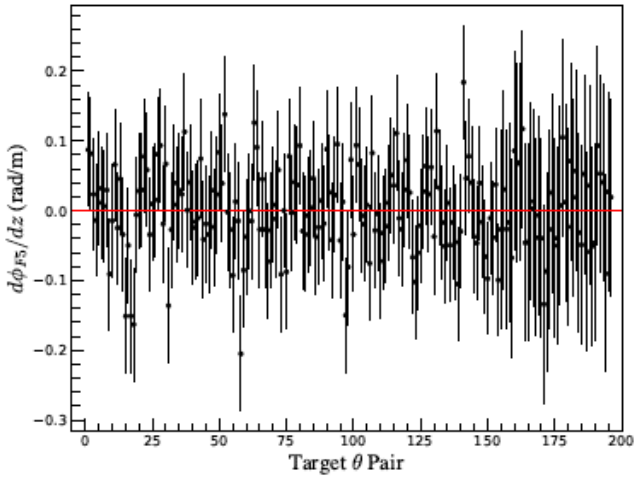


C. D. Hughes et al., J. Magn. Magn. Mater. **629**, 173273 (2025)

Spin Rotation Apparatus

ORNL HFIR Multimodal Advance Radiography Station (MARS) at beamline CG-1D, with a neutron spin interferometer to look for (neutron) spin-(electron) spin interactions



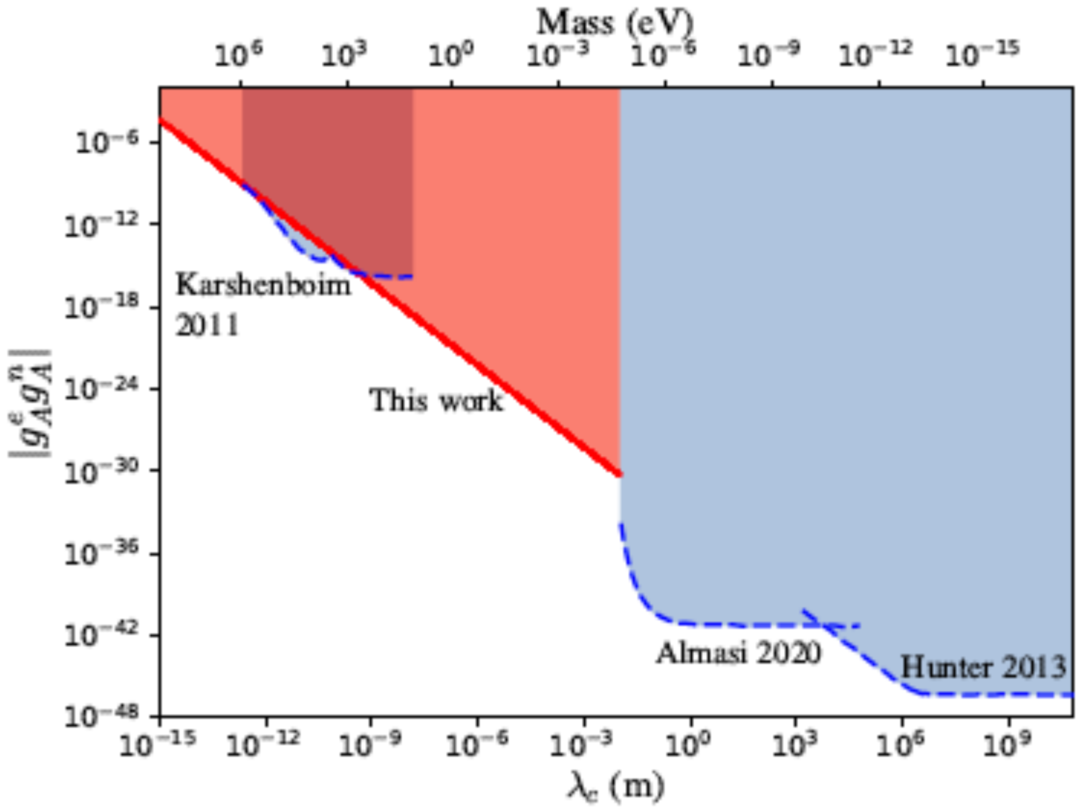


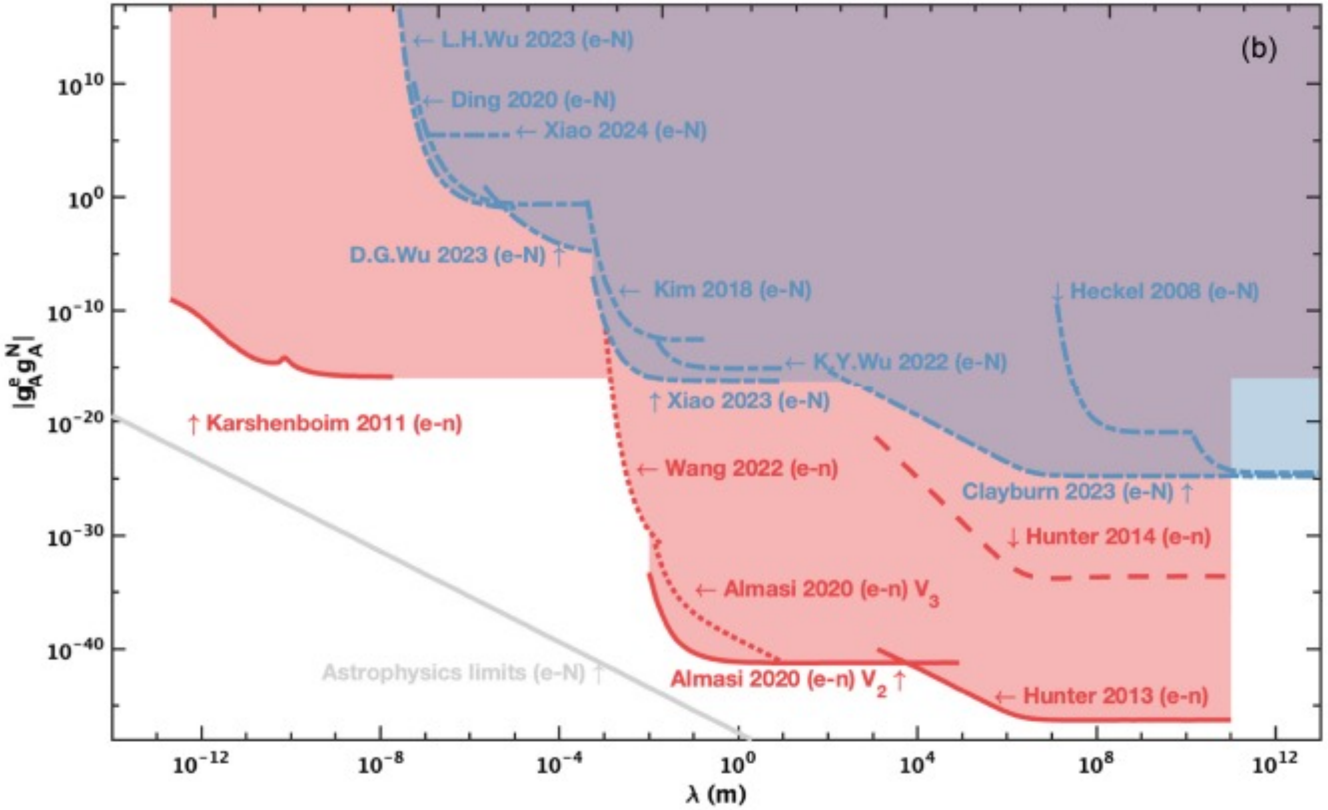
New Constraints on $g^e_A g^n_A$ in mm-Angstrom range

We will also constrain $g^e_P g^n_P$

New data from MARS, beamtime on SNS NSE (2026)

Can be improved by 2-3 orders of magnitude in future





T. Mulkey et al., **Upper Bound on Exotic Polarized Neutron/Polarized Electron Interactions**, PRL **136**, 071801 (2026).

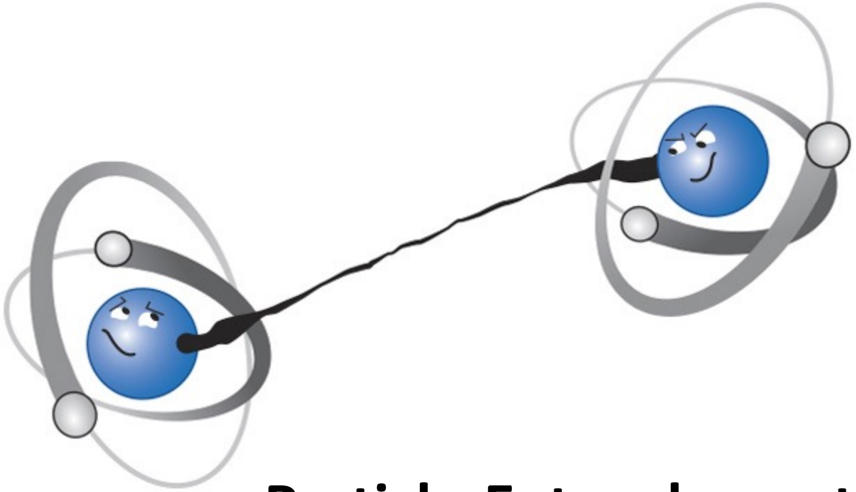
From L. Cong et al, Rev. Mod. Phys. 97, 025005 (2025)

Two Quantum Entanglement "Flavors"

An entangled quantum state cannot be written as a separable product:

either of one degree of freedom of 2 or more particles,

***or** more than one degree of freedom of one particle.*



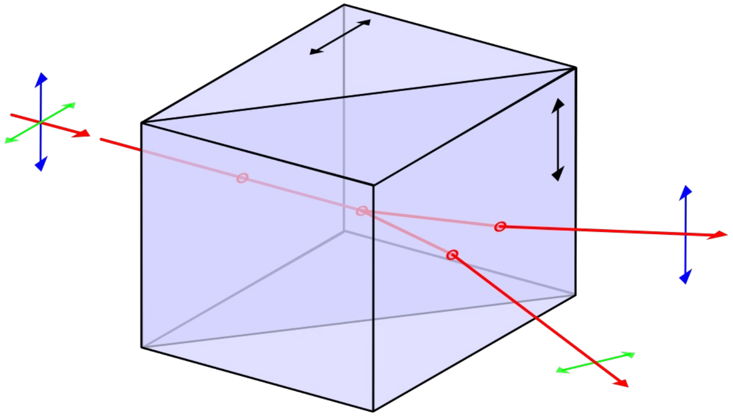
Particle-Entanglement

Entangled Spin State of Two Particles

$$|\psi_{Bell}\rangle = \frac{1}{\sqrt{2}}(|\uparrow\rangle|\downarrow\rangle + |\downarrow\rangle|\uparrow\rangle)$$

Mode- Entangled State in Spin and Momentum of One Particle

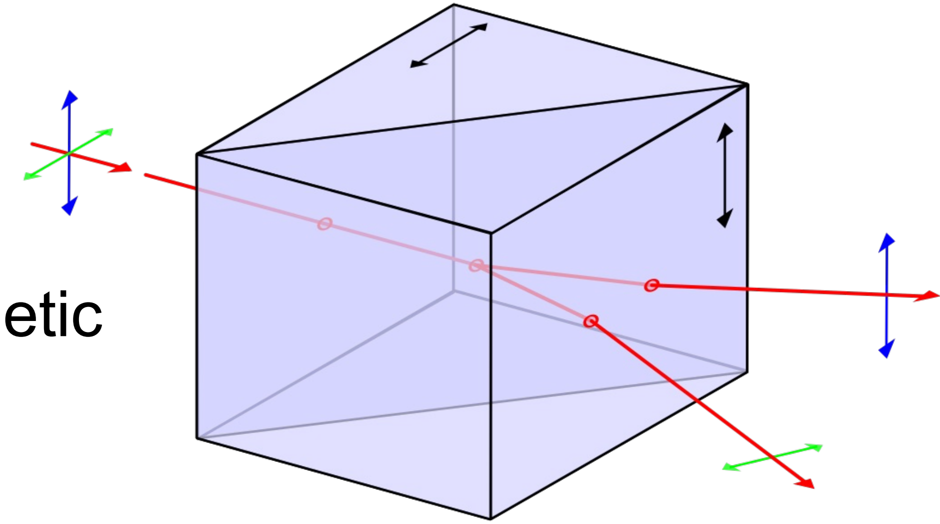
$$|\psi\ \ \rangle = \frac{1}{\sqrt{2}}(|\uparrow\rangle|P1\rangle + |\downarrow\rangle|P2\rangle)$$



Mode-Entanglement (Wollaston Prism for light)

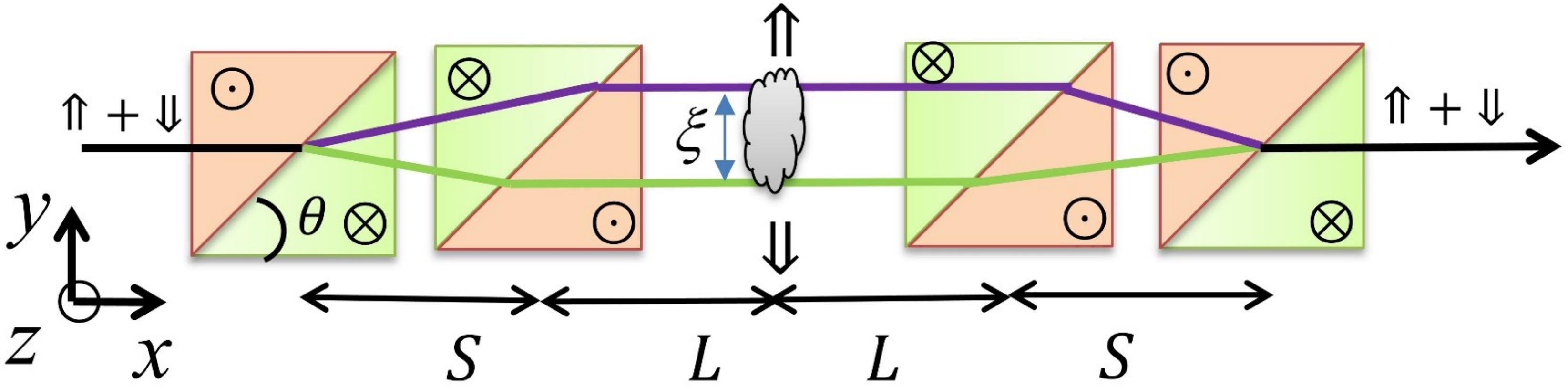
(Polarized) neutron beamsplitters for interferometry

A Wollaston prism for light sends 2 orthogonal photon polarizations in different directions



We can make the same things for neutrons using magnetic field gradients (just Stern-Gerlach with sideways spin!)

Two pairs together make an interferometer with adjustable, mode-entangled neutron spin polarization

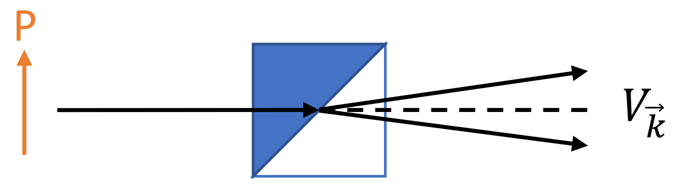


F. Li et al; Rev. Sci. Instrum., **85**, 053303 (2014)

Two Types of Mode-Entangled State Preparation Using Magnetic Field Gradients

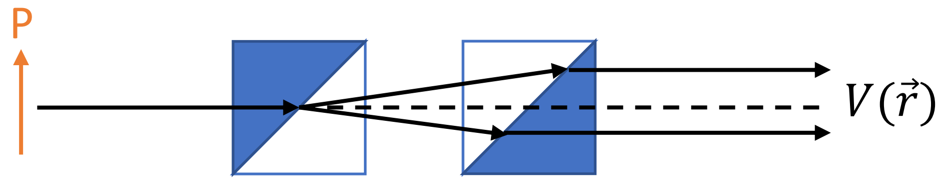
Entanglement between spin and momentum

- $|\psi_i\rangle = |\uparrow\rangle \otimes |\vec{k}\rangle + |\downarrow\rangle \otimes |\vec{k} + \delta\vec{k}\rangle$

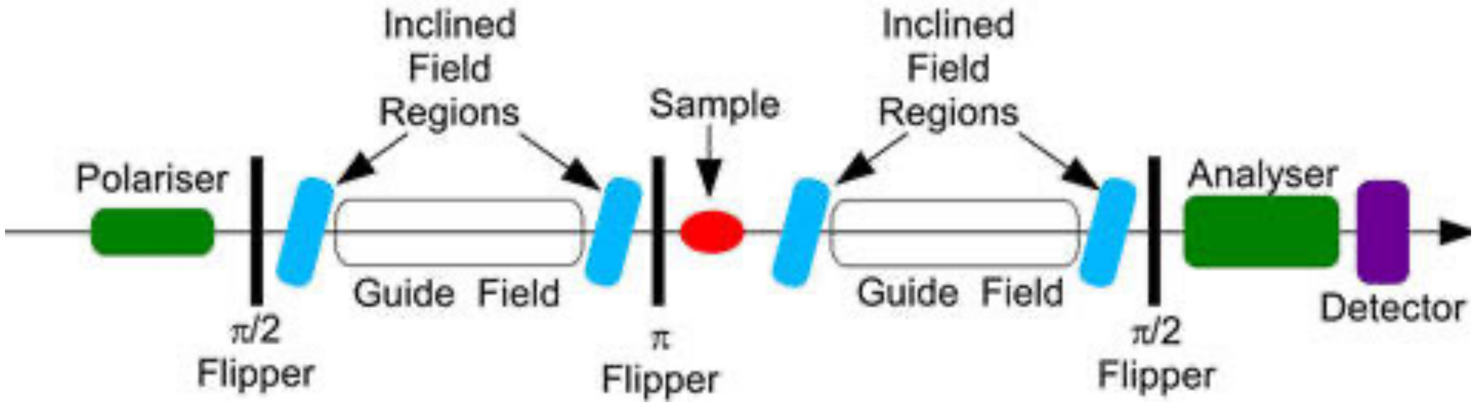


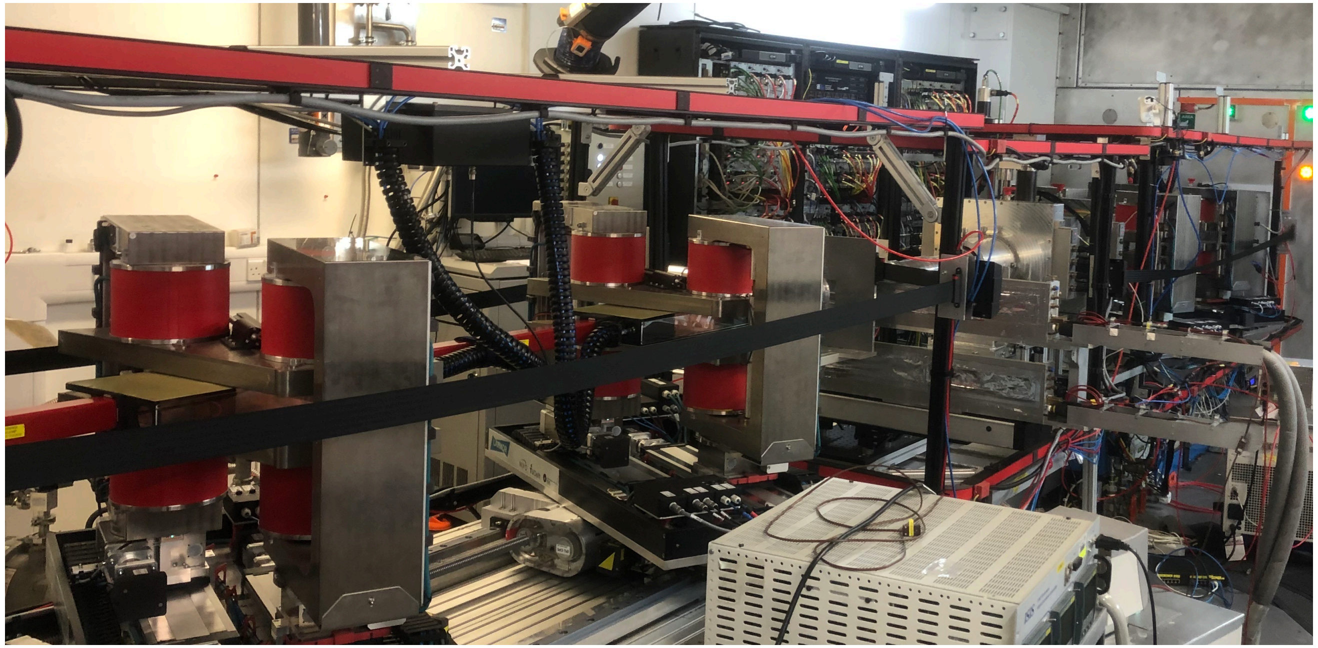
Entanglement between spin and spatial separation

- $|\psi_i\rangle = |\uparrow\rangle \otimes |path\ I\rangle + |\downarrow\rangle \otimes |path\ II\rangle$



ISIS Path-Encoded Neutron Spin Echo Devices

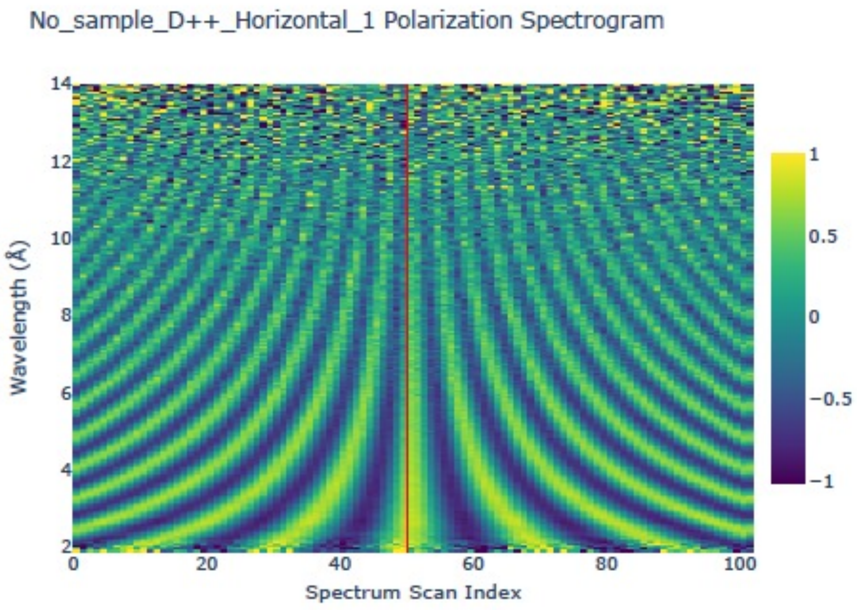


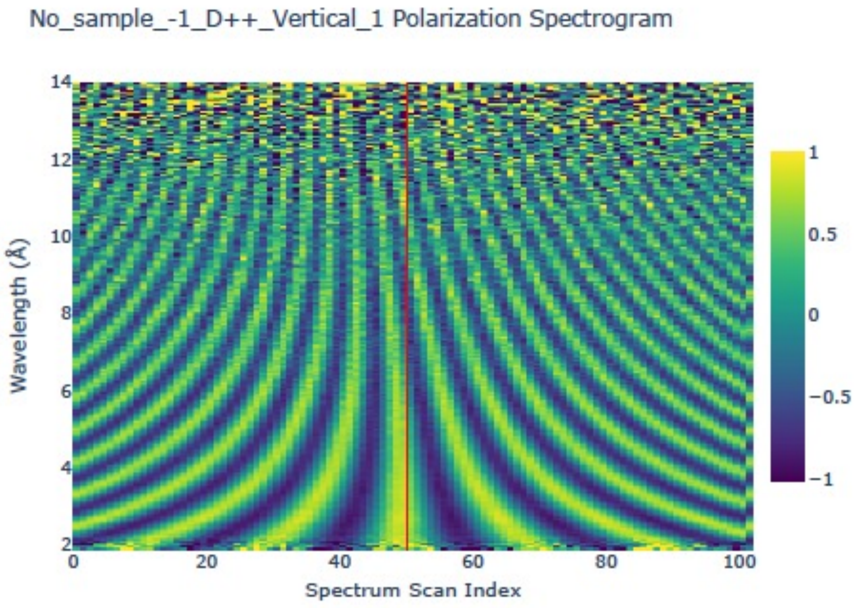


- Larmor and Offspec, both on ISIS TS-II target
- ~2-14 Angstrom polarized neutrons
- Spin-echo capabilities using RF flippers
- **Offspec – rotates encoding direction**

S. Parnell

Neutron interference fringes in a path-encoded interferometer


No_sample_D++_Horizontal_1 Polarization Spectrogram


No_sample_-1_D++_Vertical_1 Polarization Spectrogram

K. Steffen, PhD thesis, Indiana U (2024)

Slower neutron spins precess more in B

Interference fringe spacing changes with neutron speed

At pulsed neutron source, fringes mapped out using the neutron time-of-flight to detector

If the interferometer paths are at different gravitational potentials: the fringes “tilt”

Test of CPT/Lorentz violation in spin-gravity coupling (analysis in progress)

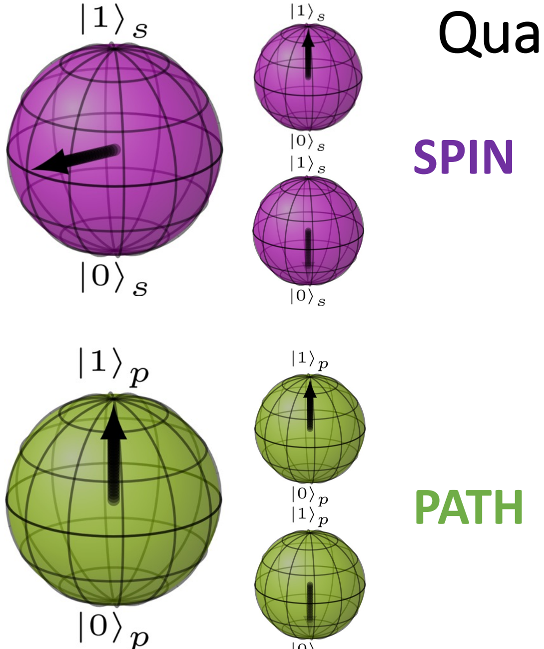
Certification of entanglement

1. Observables of mode-entangled systems can violate Bell-like inequalities
   - This violation tests the *contextuality* of the probe, the observable is called an *entanglement witness*
2. Goal: Confirm our claim that our neutron beams are mode-entangled
3. Use phase-shifting components to test contextuality:
   - Spin shifter: electromagnetic coil introduces spin phase
   - Path phase shifter: quartz crystal path length

cf.

- Hasegawa et al, *Nat.*, **425**, 45-48 (2003)
- Hasegawa et al, Phys. Rev. A **81**, 032121 (2010)

Quantum Contextuality Test: 2 mode entanglement

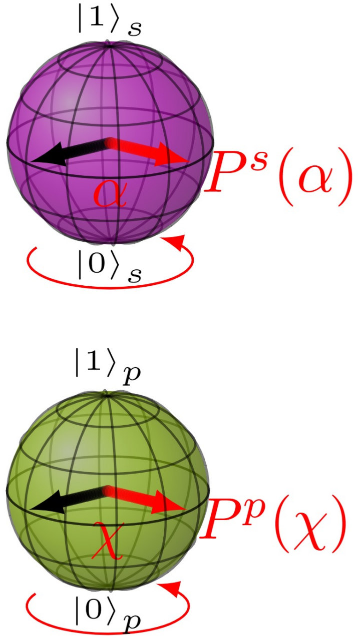


SPIN

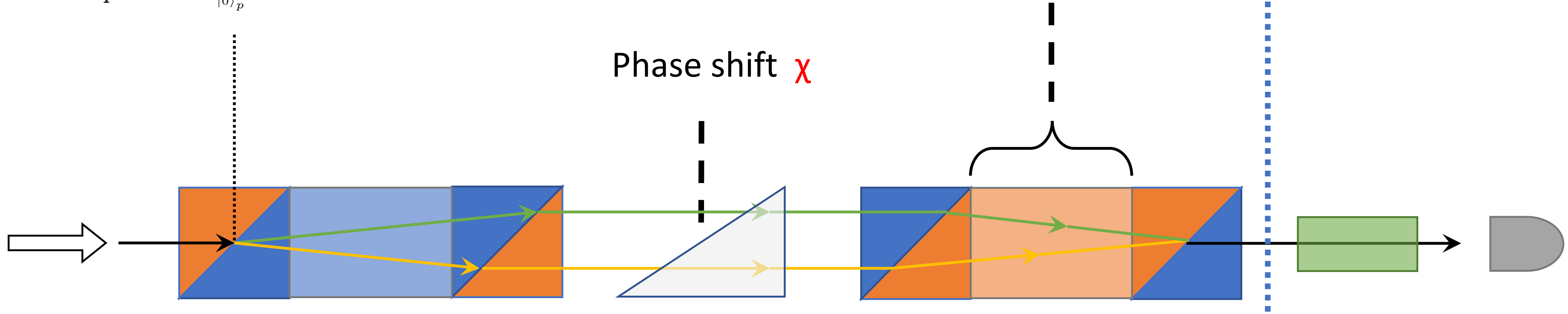
PATH

Adjust relative phases of each qubit and measure spin projections

Access the same correlations that are measured in the classic two-photon Bell tests



Phase shift α



Phase shift χ

Beam direction

MWP1

Guide field 1

MWP2

Path phase wedge crystal χ

MWP3

Guide field 2, also phase coil α

MWP4

Spin analyzer & detector

Measurement

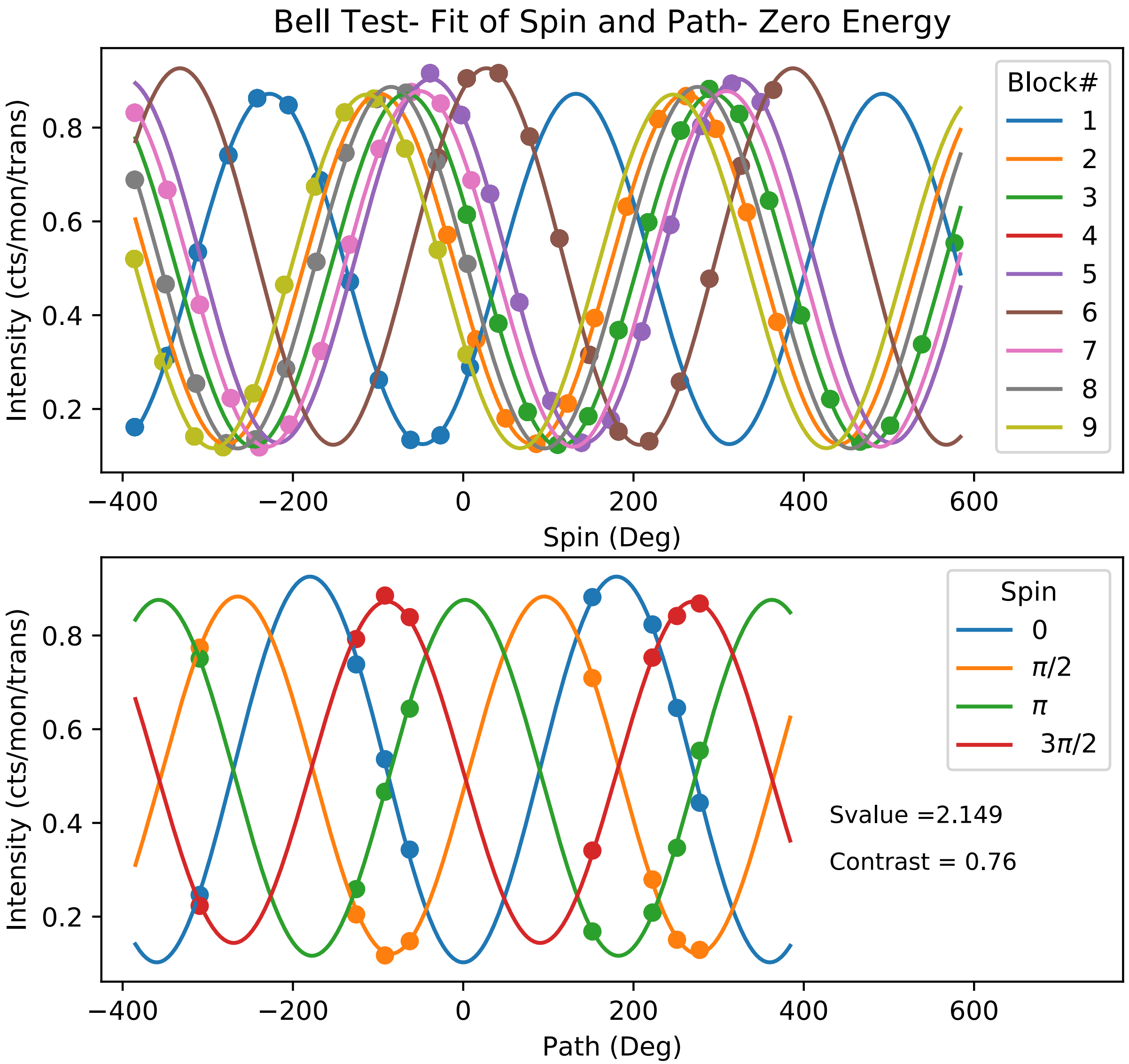
Results for 2-Variable Mode Entanglement

- Classical value: S=2
- QM predicts $S=2\sqrt{2}$ for polarization P of 1

- We get S=2.16 +/- 0.02 with P=0.77:

QM predicts S=2.18

- Conclusion: this neutron beam is mode-entangled



Bell Test- Fit of Spin and Path- Zero Energy

J. Shen *et al*, *Nat. Comm.*, **11**, 930 (2020)

(Optical) Sagnac Effect

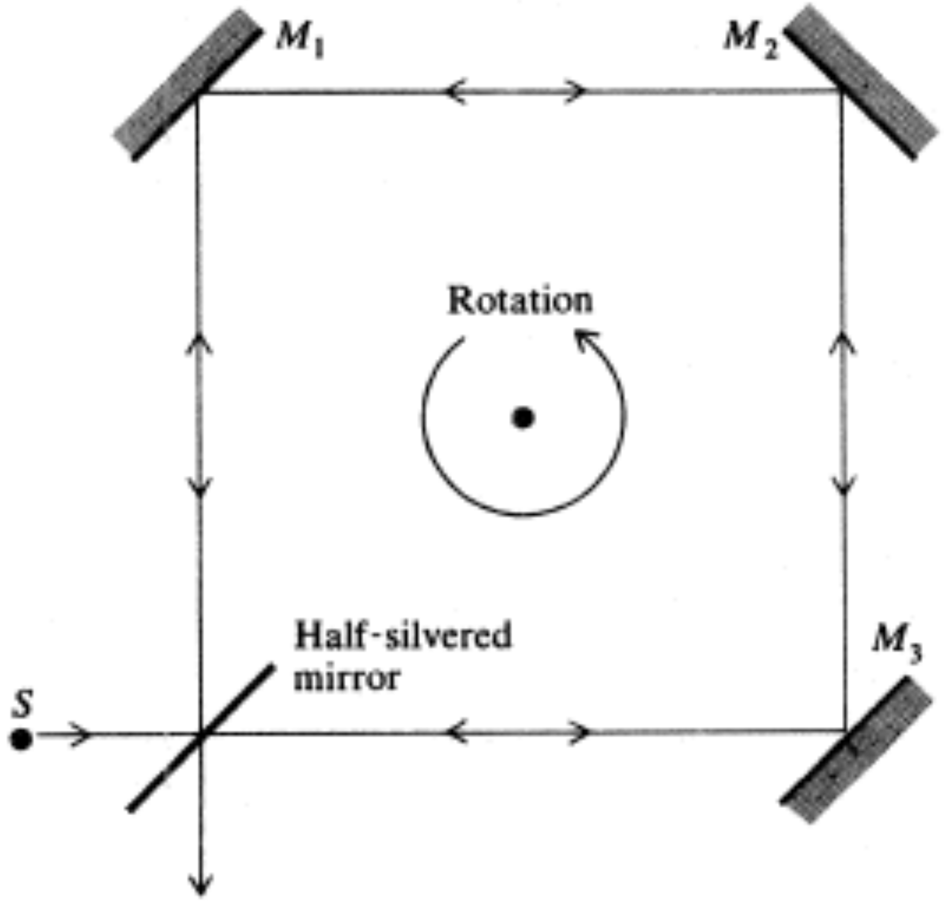


Diagram of Sagnac's experiment.

Three mirrors and one beamsplitter/recombiner

The two interfering paths circulate clockwise and counterclockwise around the apparatus

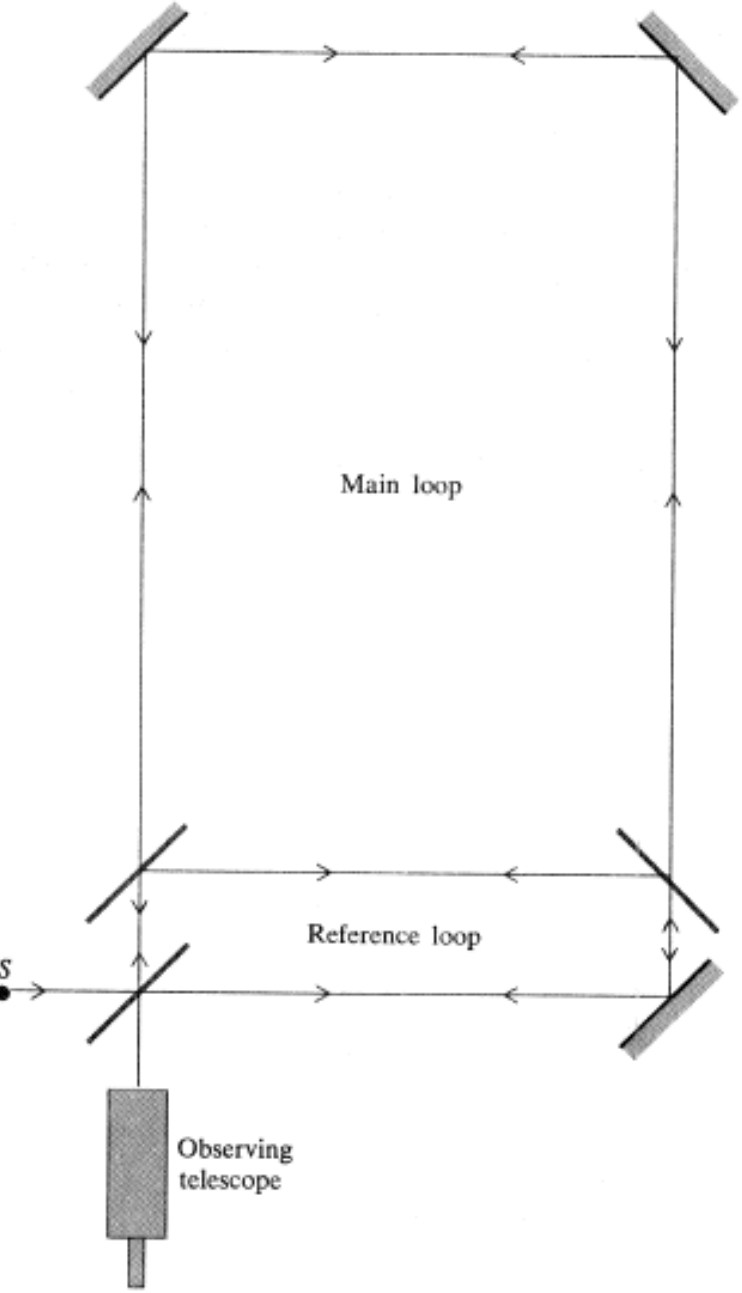
If interferometer is rotating with angular velocity ω, phase shift proportional to $\boldsymbol{\omega} \cdot \boldsymbol{L}$, where L is the angular momentum on one of the paths

Michelson-Gale-Pearson Experiment (1925)

- Rectangular Sagnac interferometer, **612 m x 339 m (!)**

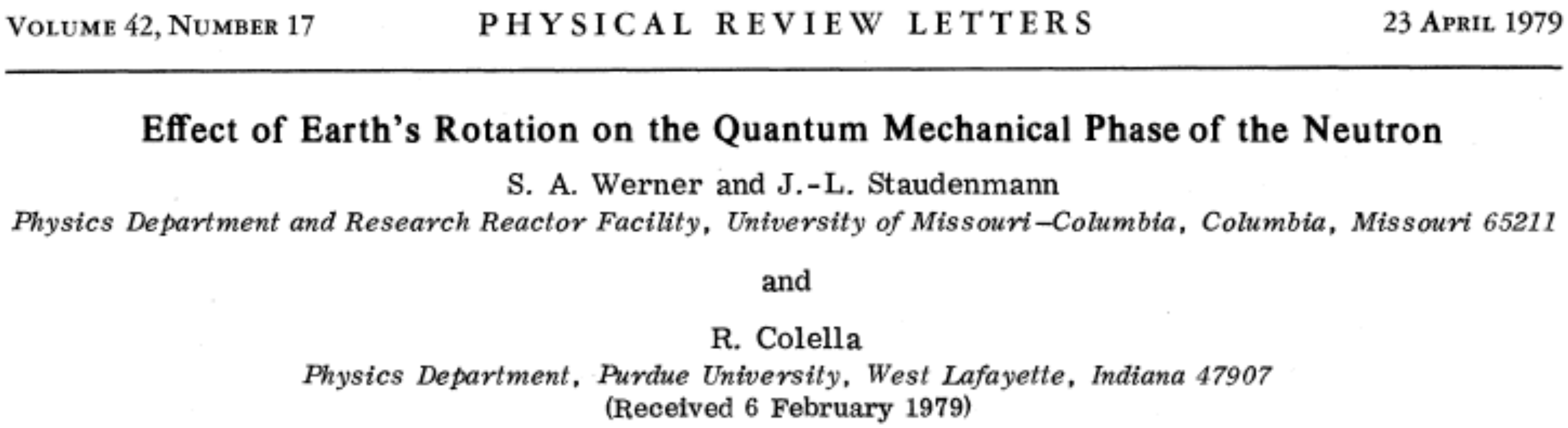
- Arms built from 12-inch evacuated sewer pipe

- Observed the fringe shift expected from earth’s rotation



The Michelson-Gale experiment for detecting the absolute rotation of the earth.

Neutron Sagnac Effect



VOLUME 42, NUMBER 17 PHYSICAL REVIEW LETTERS 23 APRIL 1979

Effect of Earth's Rotation on the Quantum Mechanical Phase of the Neutron

S. A. Werner and J.-L. Staudenmann
Physics Department and Research Reactor Facility, University of Missouri–Columbia, Columbia, Missouri 65211

and

R. Colella
Physics Department, Purdue University, West Lafayette, Indiana 47907

(Received 6 February 1979)

$\omega \cdot L$ changed by rotating the perfect xtal interferometer about the vertical axis

First observation of the Sagnac effect for matter waves

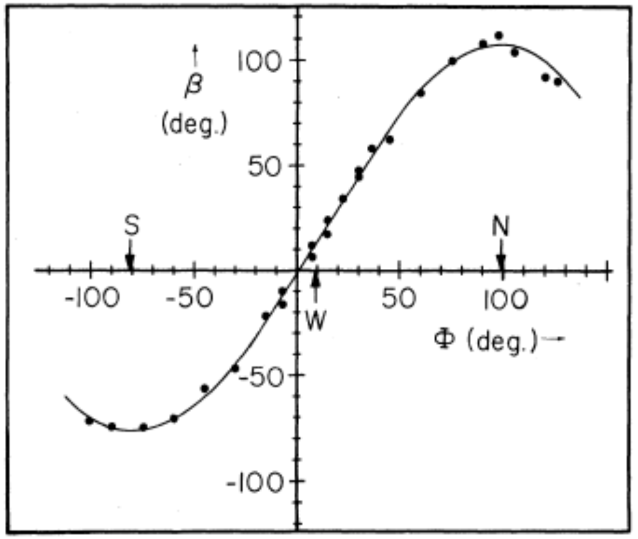
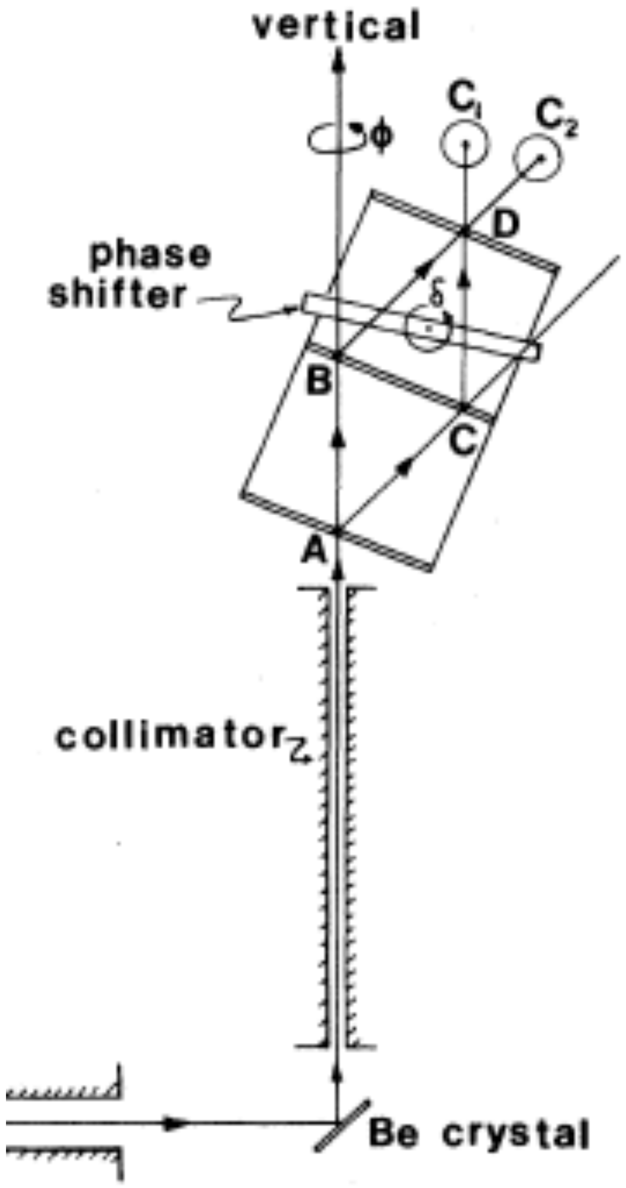
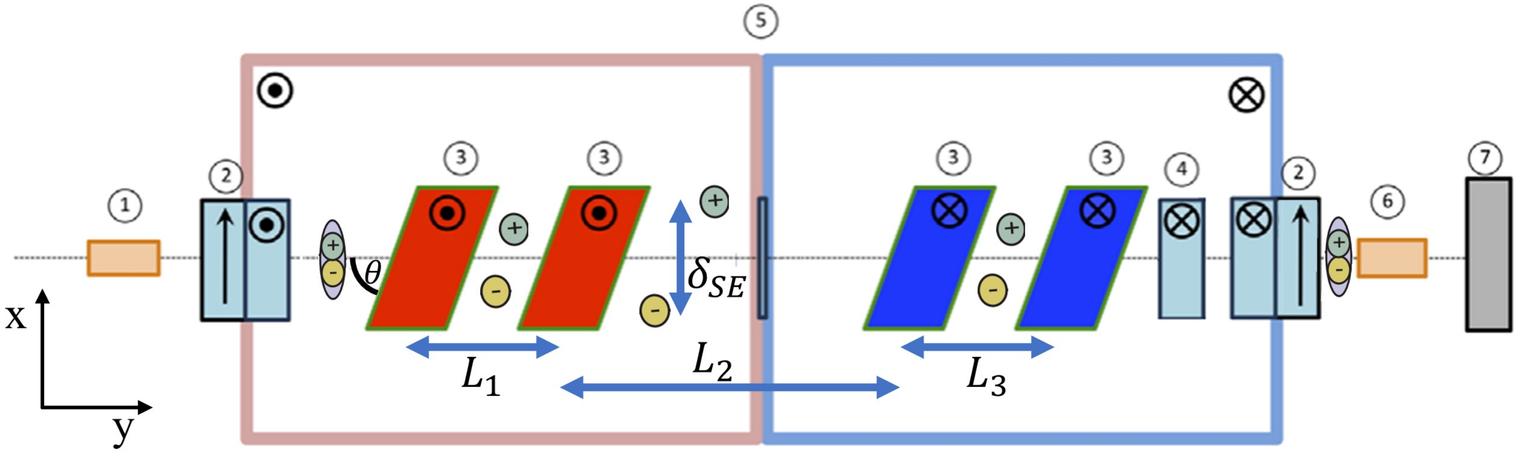
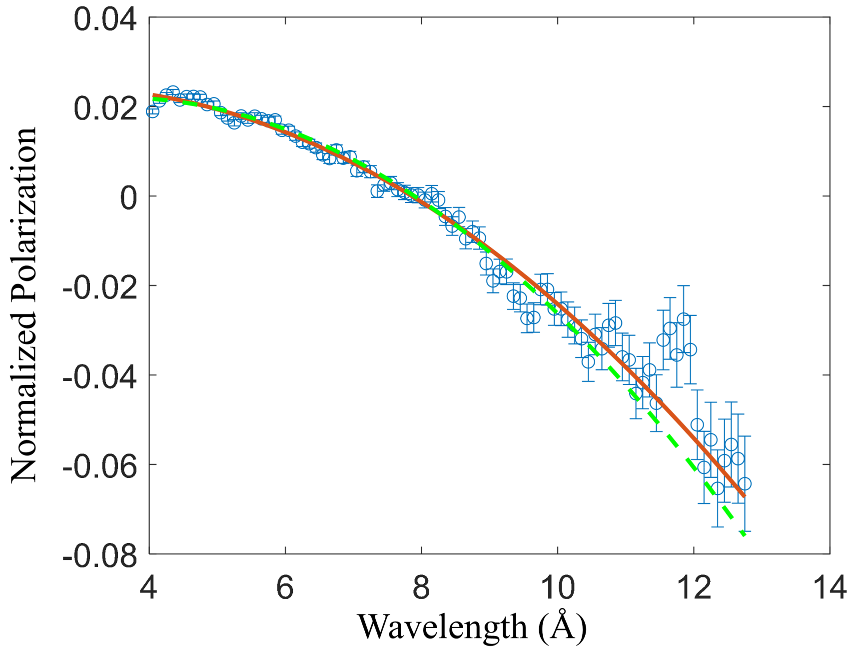


FIG. 3. A plot of the phase shift β due to Earth's rotation as a function of the orientation φ of the normal area $\vec{A}$ of the interferometer about a vertical axis. The symbols N, W, and S indicate north, west, and south.



Neutron Sagnac Effect at ISIS





Sagnac phase shift isolated by characteristic λ^2 neutron wavelength dependence in interferometer

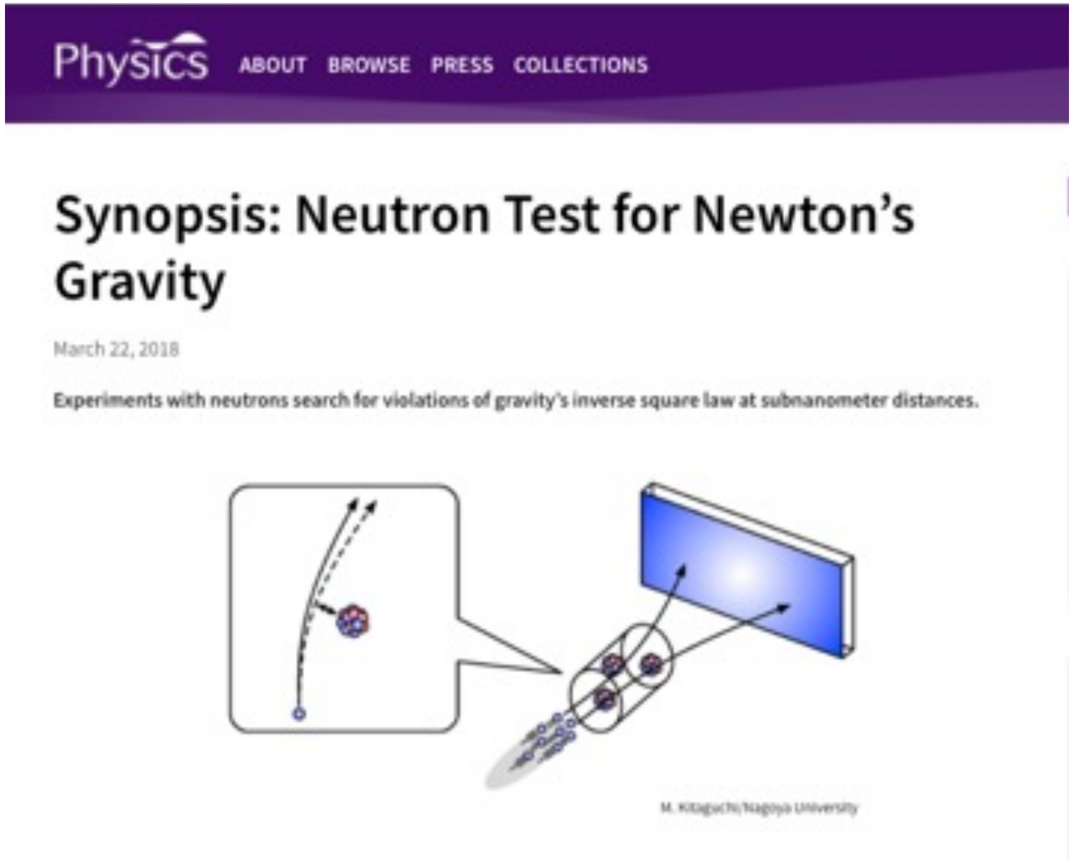
Sensitivity 10^5 better than Werner et al

Paves the way to measure the neutron Sagnac effect in the quantum limit ($L \sim \hbar$)

N. Geerits et al., **Measuring the Angular Momentum of a Neutron Using Earth's Rotation**, Phys. Rev. Res. **7**, 013046 (2025).

Dark energy scale -> 100 micron length scale

Is gravity weak because it leaks into extra dimensions?



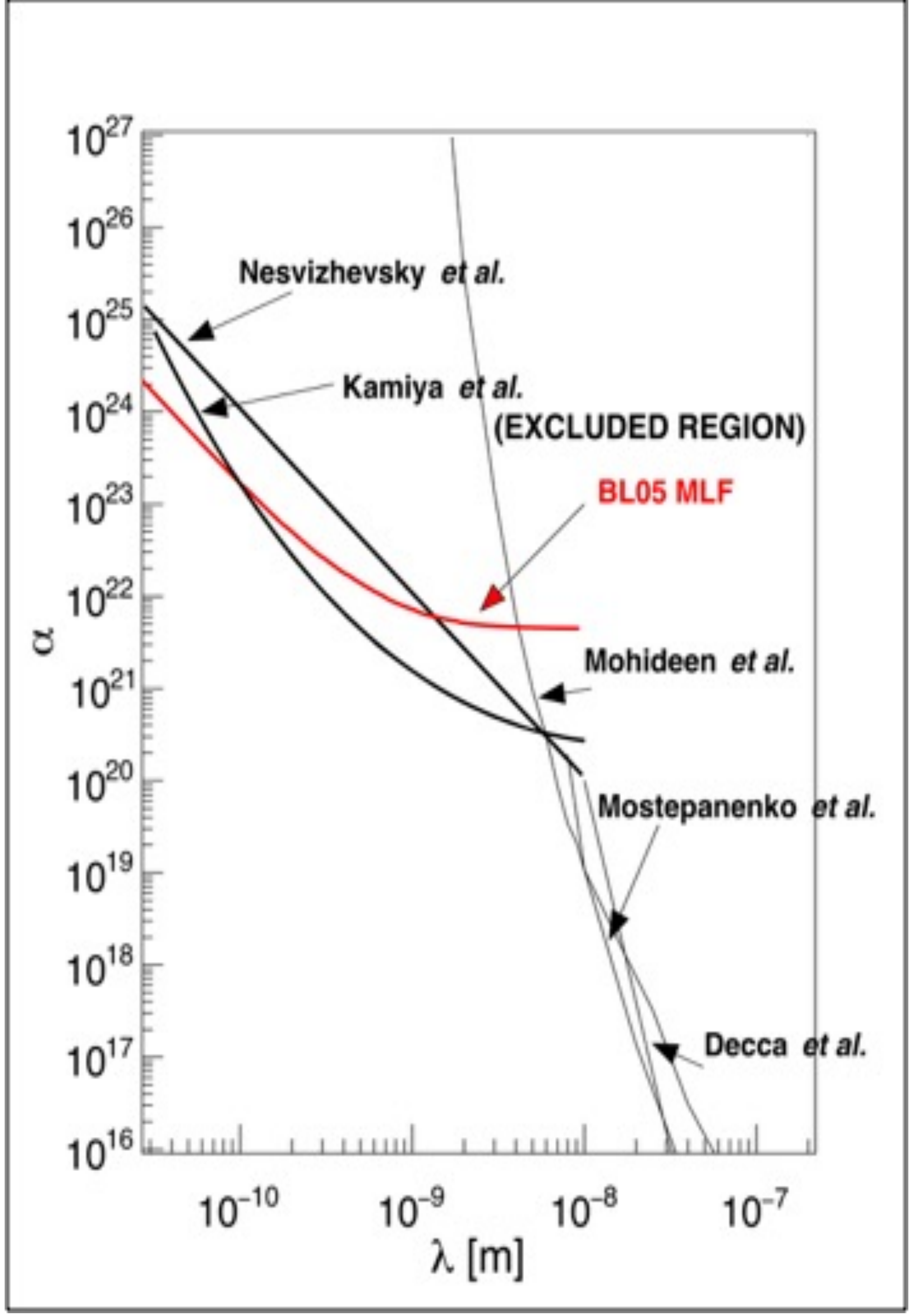
Synopsis: Neutron Test for Newton's Gravity

March 22, 2018

Experiments with neutrons search for violations of gravity's inverse square law at subnanometer distances.

M. Kitaguchi/Nagoya University

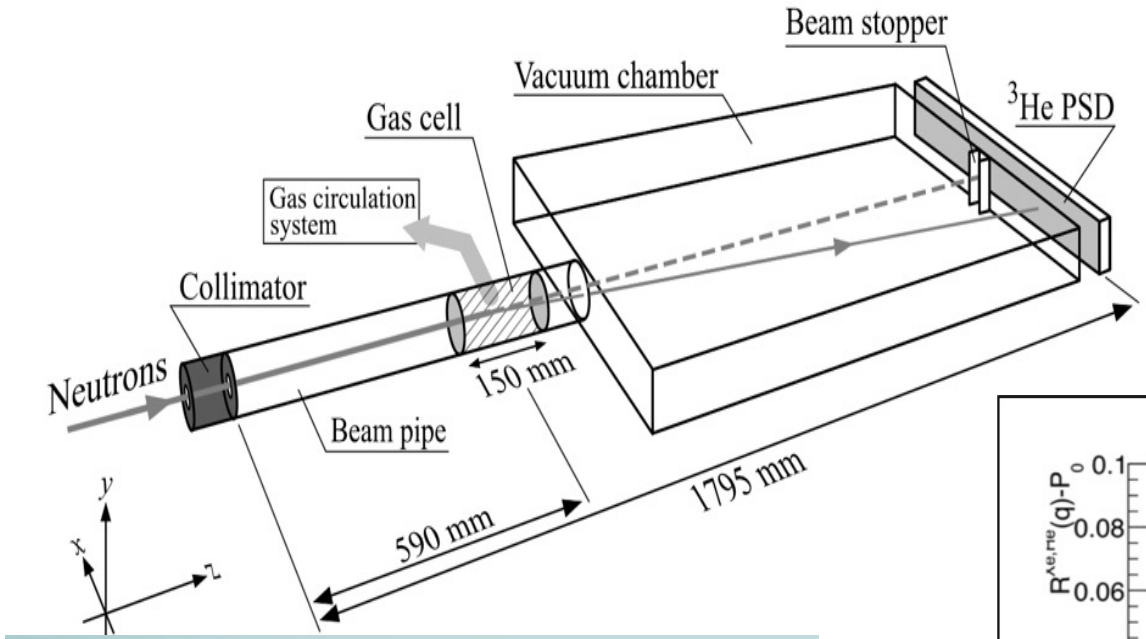
C. Haddock et al., **A search for deviations from the inverse square law of gravity at nm range using a pulsed neutron beam,** Phys. Rev. D **97**, 062002 (2018).



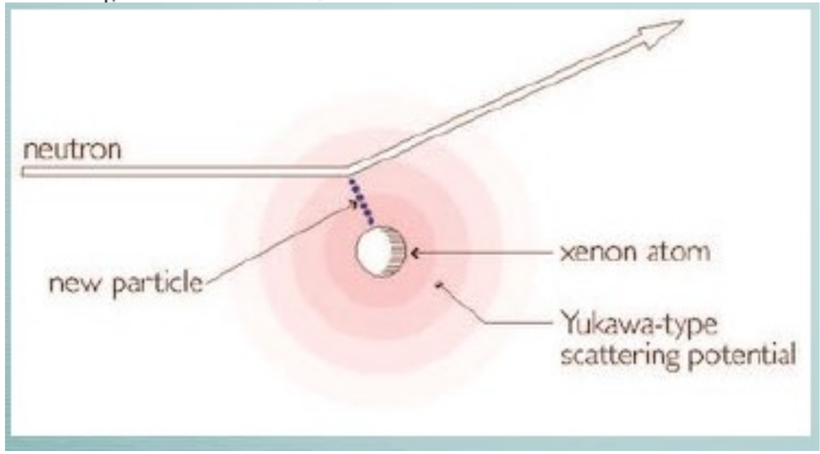
best neutron limit for at a range of 10^{-11} m at the time

Later work improved it

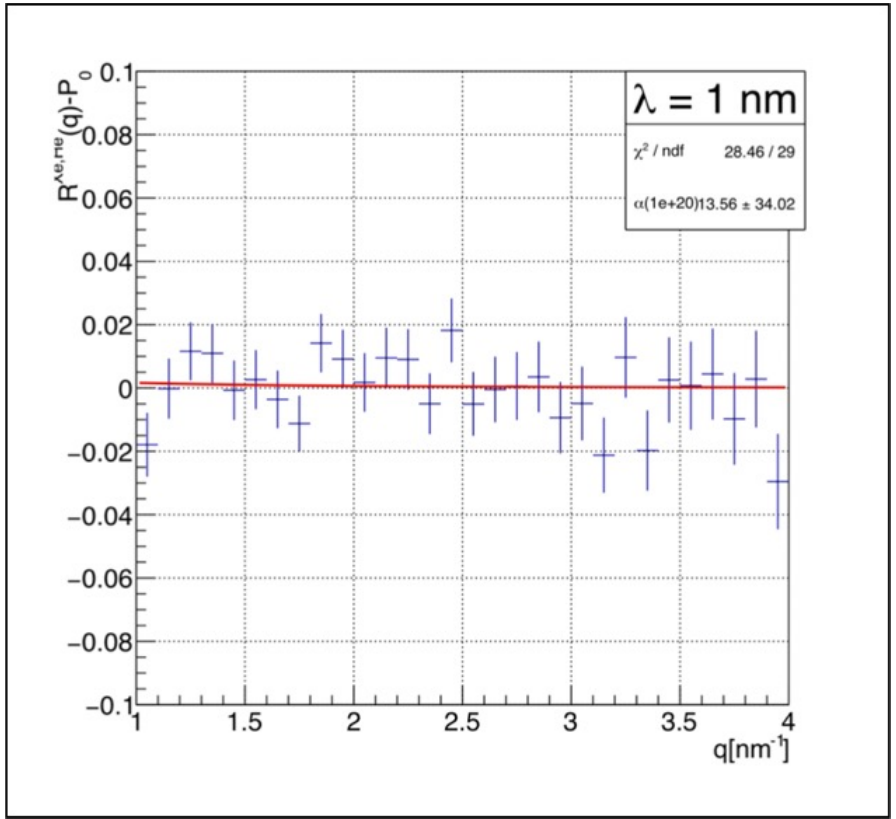
Idea and Experimental Layout



Look at angular distribution of neutron scattering from an ideal gas



$$V(r) = G\frac{m_1 \cdot m_2}{r}(1+\alpha \cdot e^{-r/\lambda})$$



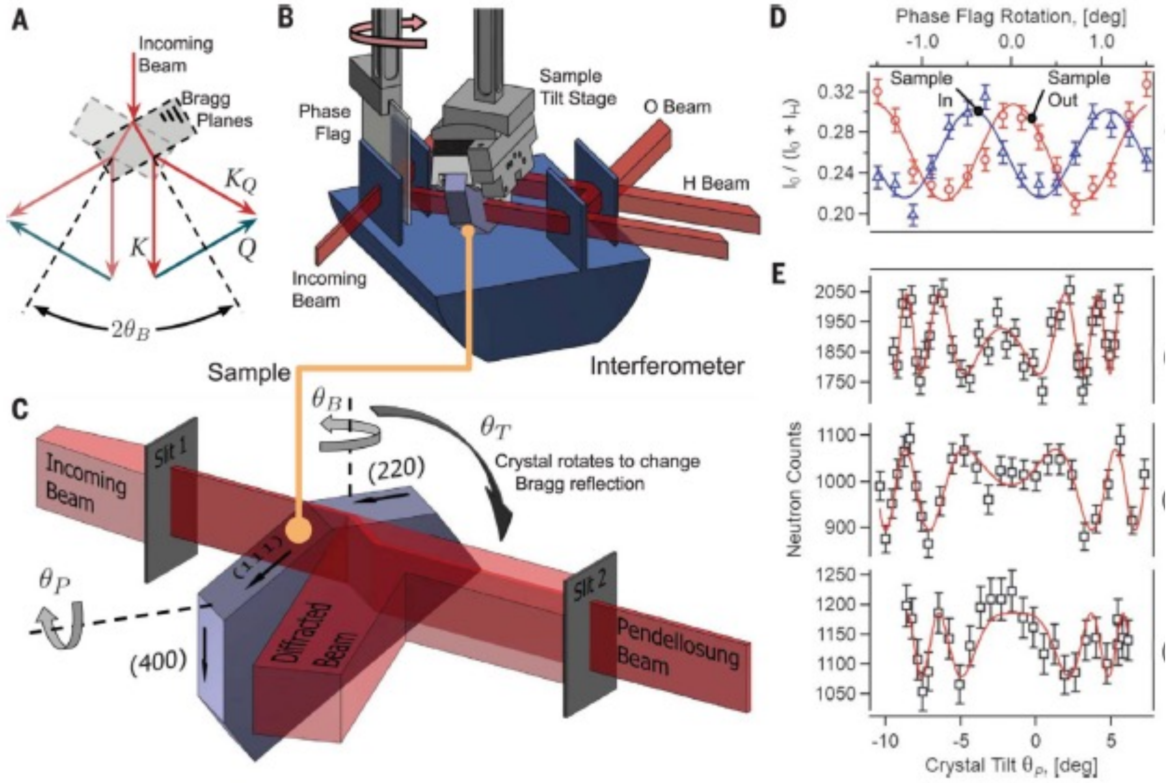


Fig. 1. Pendellösung interference in silicon.

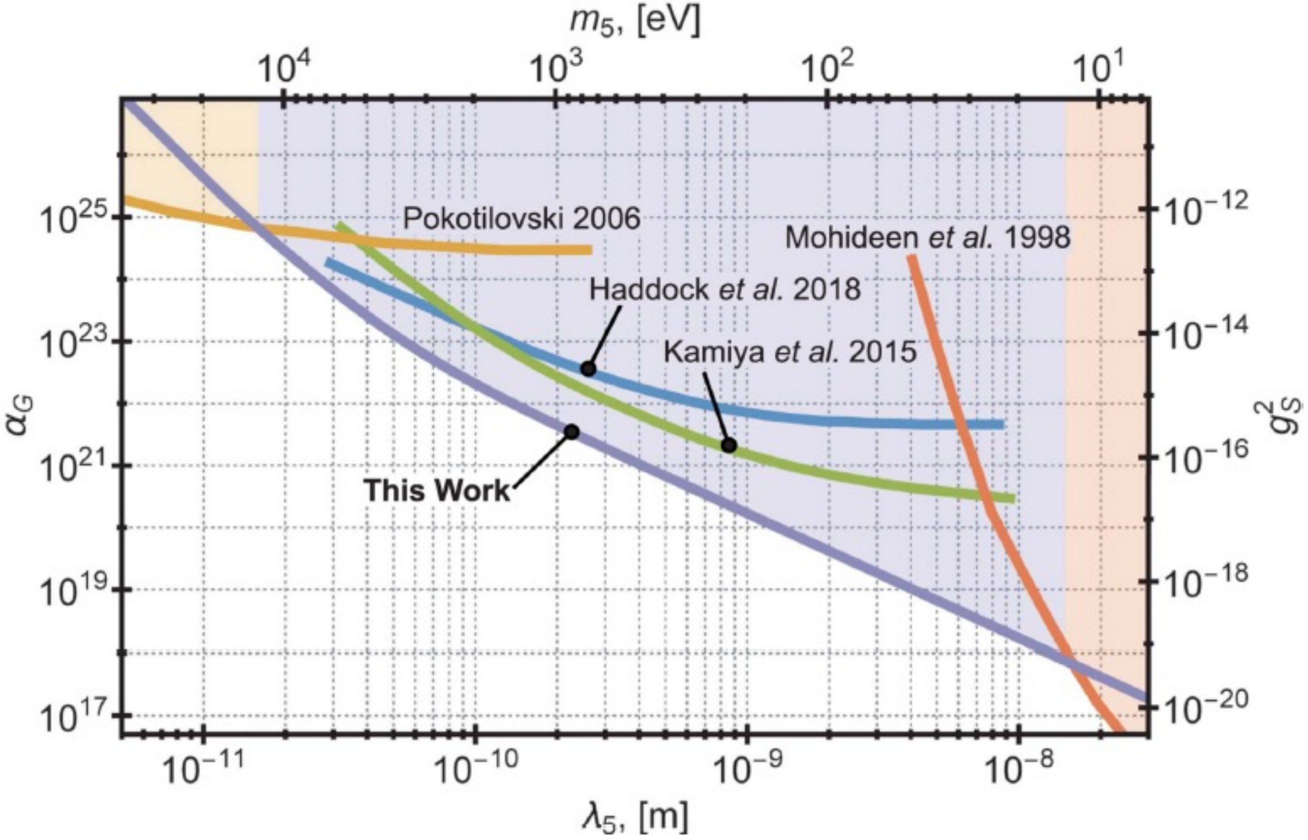


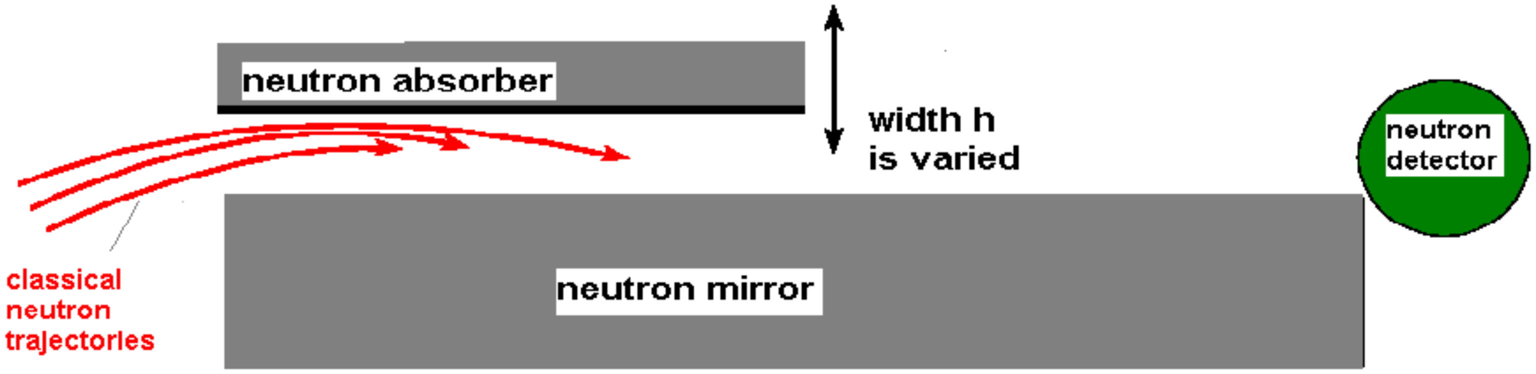
Fig. 3. Limits (95% confidence) on the strength of a Yukawa modification to gravity α_G compared with previous experiments as a function of the force's range λ_5. The same limits constrain the coupling to nucleon number g_S^2 of a yet-undiscovered scalar with mass m_5. The shaded region is excluded. Other limits shown are those of Pokotilovski 2006 (56), Mohideen *et al.* 1998 (60), Haddock *et al.* 2018 (55), and Kamiya *et al.* 2015 (54).

Precision measurement using neutron dynamical diffraction in perfect silicon xtals. Interference between different neutron paths ("Pendullosung oscillations")

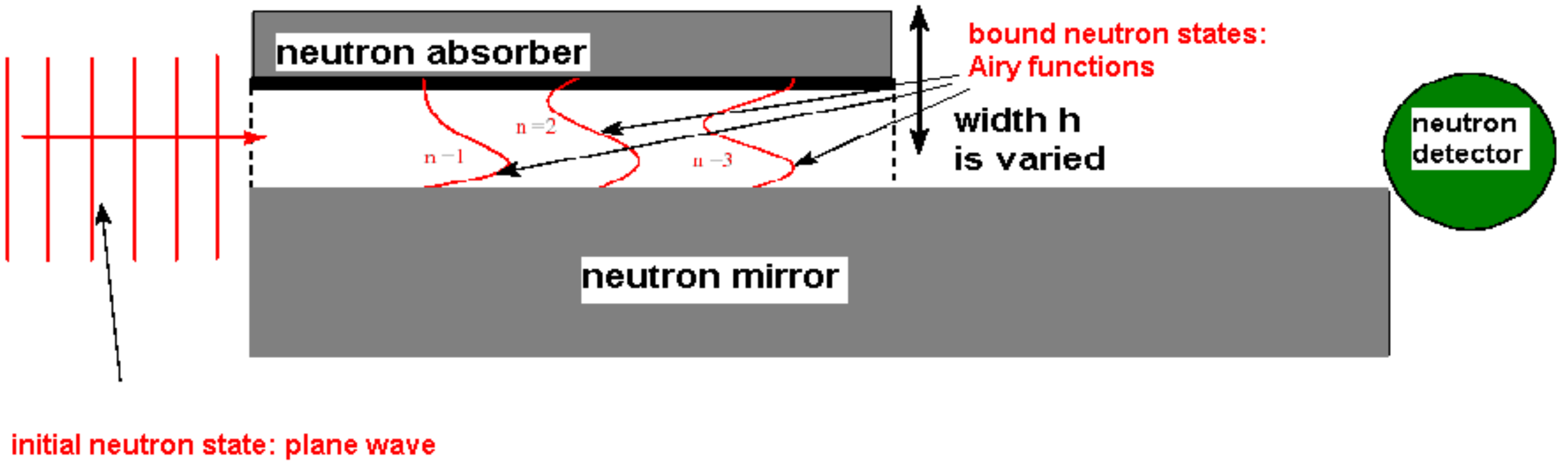
B. Heacock et al., **Pendulossung interferometry probes the neutron charge radius, lattice dynamics, and fifth forces, Science 373**, 1239-1243 (2021).

Classical/QM Bouncing Neutrons

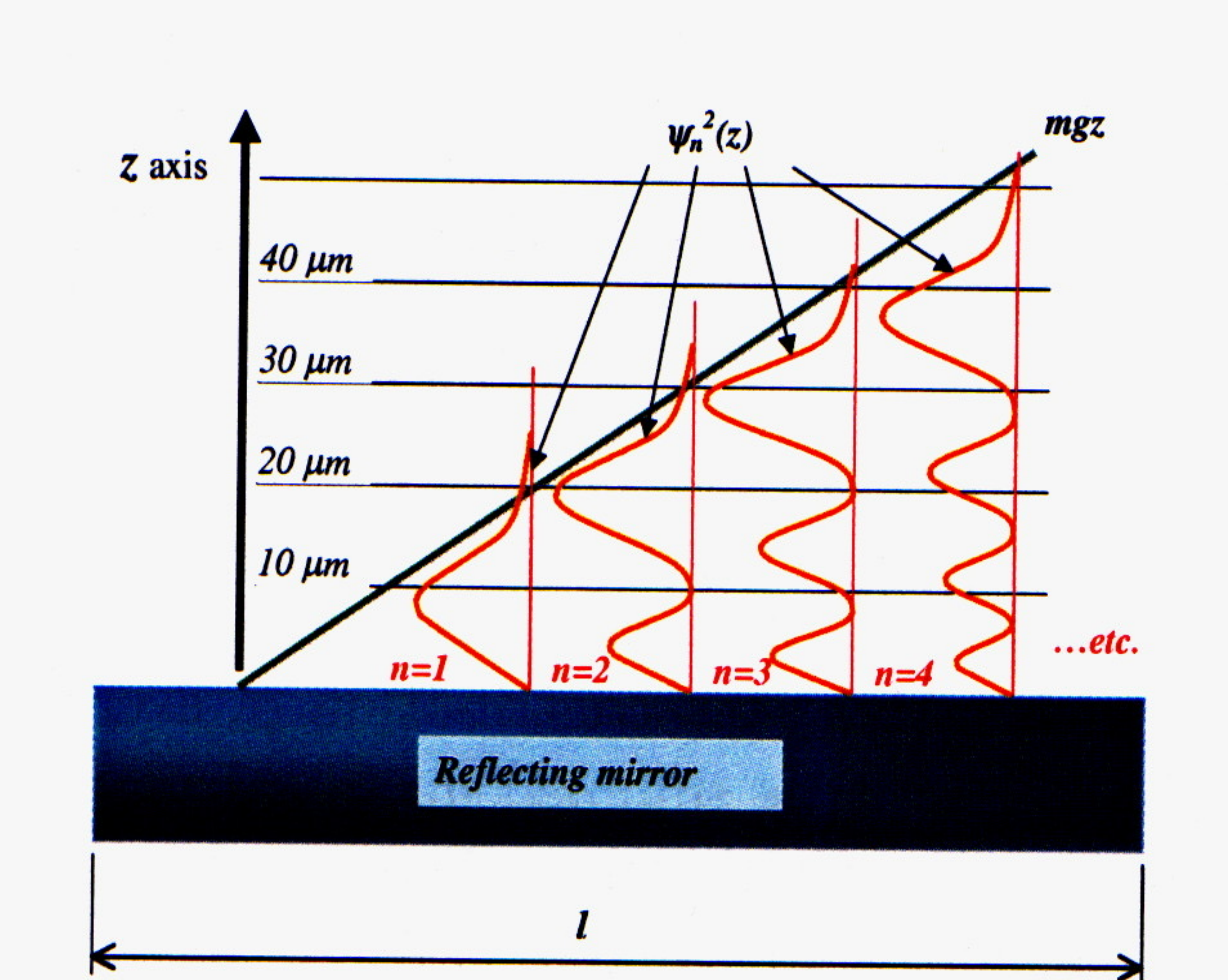
Classical View



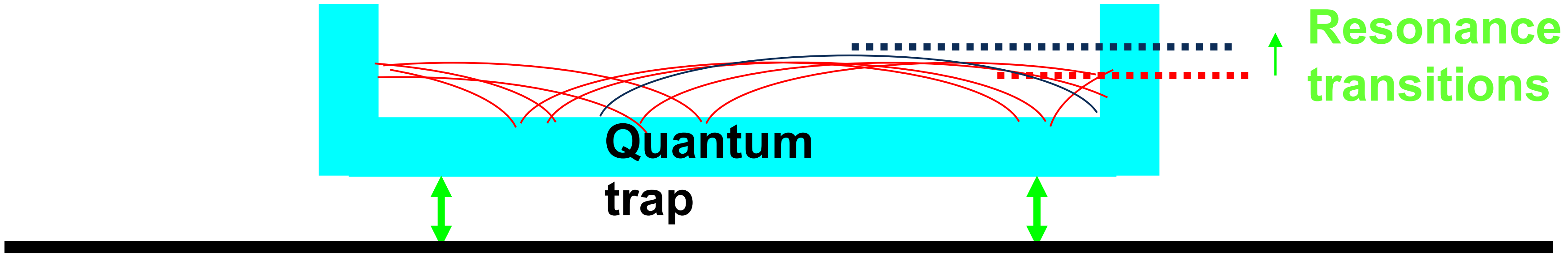
Quantum View



Neutron Probability Distributions Above the Mirror



Gravitational Resonance Spectroscopy: Applications in fundamental physics



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

-Verification of electrical neutrality of neutrons

-Gravitational physics

Interference of neutrons in different gravitational bound states observed!

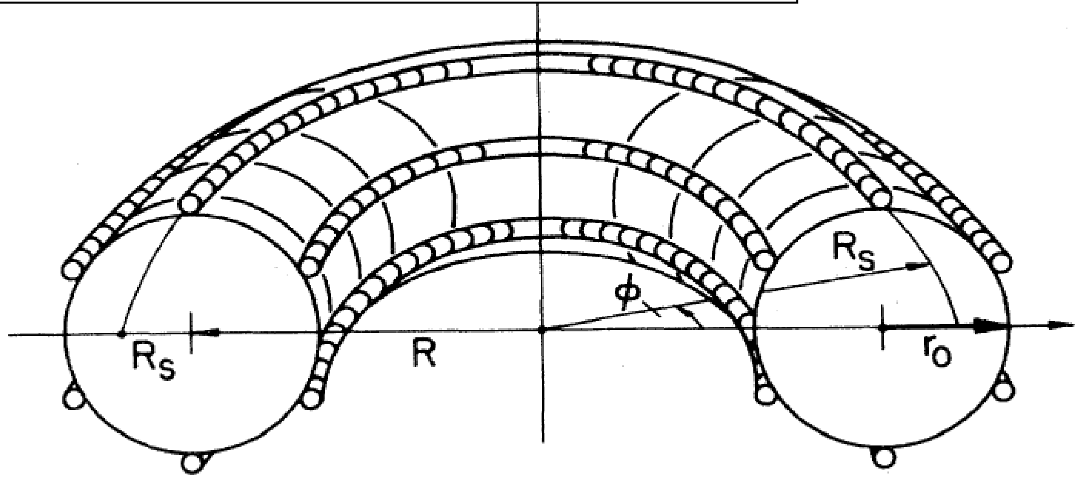
V. Nesvizhevsky, H. Abele, …

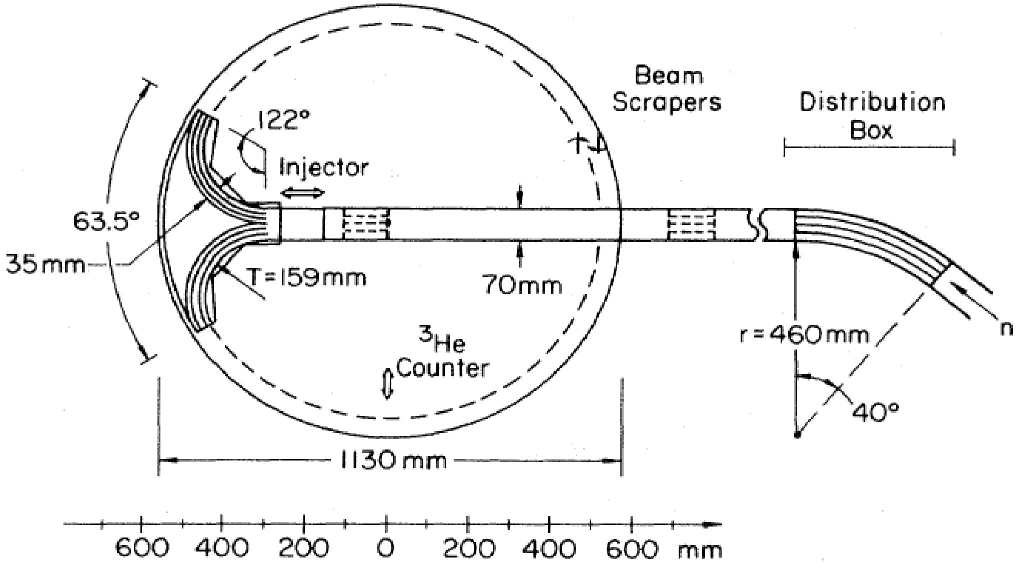
A Neutron Storage Ring?

NEutron STOrage Ring (NESTOR) developed by Nobel laureate Wolfgang Paul and colleagues

stored 1-2 μeV neutrons at the Institut Laue-Langevin (ILL) in Grenoble, France

Developed to measure the neutron lifetime





K.-J. Kügler, K. Moritz, W. Paul, U. Trinks, Nestor - A Magnetic Storage Ring for Slow Neutrons", Nuclear Instruments and Methods in Physics Research Section A, 228, 240, (1985)

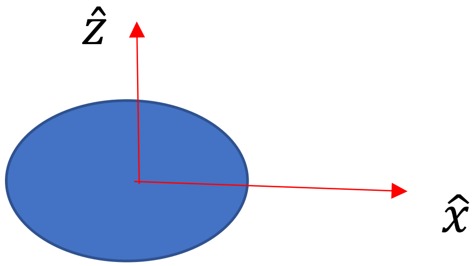
“Accelerator physics” with neutrons: just one multipole higher

$$H = -\vec{\mu} \cdot B,$$

Neutrons polarized along the magnetic field
Let the magnetic flux density in the vertical direction be

$$B_z = B_0 + B_1 x + \frac{1}{2} B_2 (x^2 - z^2),$$

B_0 dipole flux density, B_1 quadrupole field strength,
B_2 sextupole field strength.



$$\frac{dp_x}{dt} = \frac{1}{2} g_n \mu_N B_1 + \frac{1}{2} g_n \mu_N B_2 x$$

$$\frac{dp_z}{dt} = -\frac{1}{2} g_n \mu_N B_2 z.$$

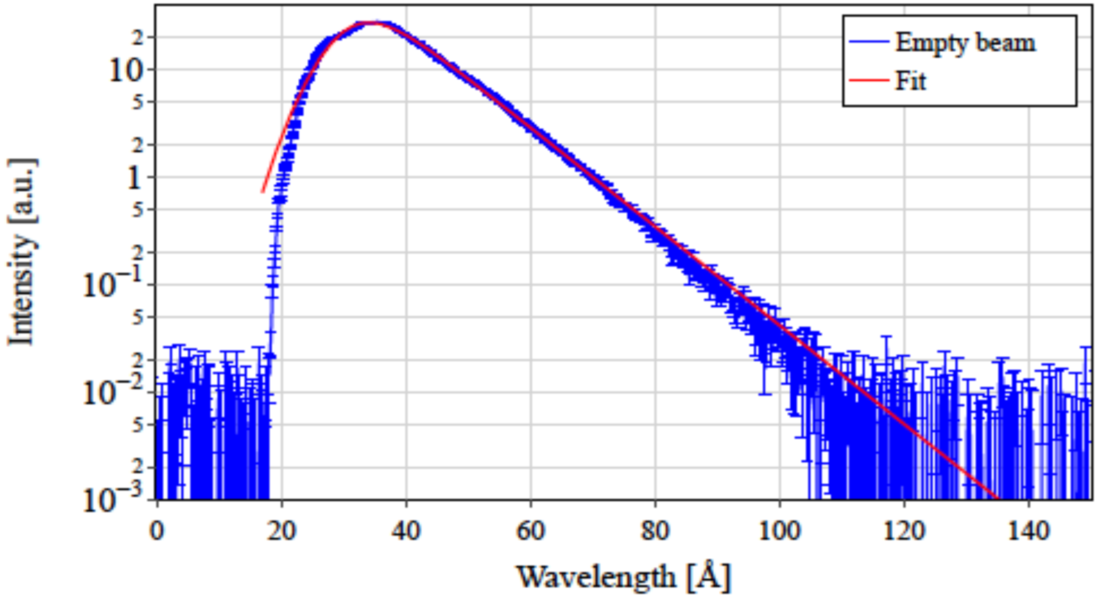
quadrupole field provides a uniform force to neutrons

sextupolar field provides a focusing or defocusing force

Can work in the 1-10 micro eV neutron energy regime

S. Y. Lee and L. K. Nguyen, **Feasibility of a strong focusing synchrotron for neutron beams,**
Phys. Rev. Accel. Beams 27, 054001 (2024)

The Dream: Phase Space Cooling of VCN



MANY more neutrons at VCN energies (1-10 microeV) just above the UCN regime

Feed these VCN into a neutron synchrotron, decelerate the neutrons with time-dependent magnetic fields, reinject into UCN experiments

Can it really be done?

Conclusions

VCN neutron beams could be employed to conduct many types of sensitive neutron interferometric measurements.

Scientific topics which would benefit from intense VCN beams include, but are not limited to

-Searches for weakly-coupled “fifth forces” of neutrons

-Investigation of noninertial effects on neutrons (Sagnac effect) in the quantum regime

-Quantum entanglement of neutrons

-A neutron storage ring

…

(some, additional) References

H. Yan, and W. M. Snow, **A New Limit on Possible Long-Range Parity-odd Interactions of the Neutron from Neutron Spin Rotation in Liquid ^{4}He**, Phys. Rev. Lett. **110**, 082003 (2013).

R. Lehnert et al, **A First Experimental Limit on In-matter Torsion from Neutron Spin Rotation in Liquid ^{4}He**, Phys. Lett. B **730**, 353 (2014).

K. Li et al., **Neutron limit on the strongly-coupled chameleon field**, Phys. Rev. D **93**, 062001 (2016).

R. Lehnert et al., **Constraining Spacetime Nonmetricity with Neutron Spin Rotation in Liquid ^{4}He**, Phys. Lett. B **772**, 865 (2017).

C. Haddock et al, **A Search for Possible Long Range Spin Dependent Interactions of the Neutron From Exotic Vector Boson Exchange,** Phys. Lett. B **783**, 227 (2018).

C. Haddock et a, **A Search for deviations from the inverse square law of gravity at nm range using a pulsed neutron beam,** Phys. Rev. D **97**, 062002 (2018).

H. E. Swanson et al, **An Upper Bound on Parity Violating Neutron Spin Rotation in ^{4}He,** Phys. Rev. C **100**, 015204 (2019).

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S. R. Parnell et al., **Search for exotic spin-dependent couplings of the neutron with matter using spin-echo based neutron interferometry**, Phys. Rev. D **101**, 122002 (2020).

S. J. Kuhn et al., **Neutron State Entanglement with Overlapping Paths**, Phys. Rev. Res. **3**, 023227 (2021).

B. Heacock et al., **Pendulossung interferometry probes the neutron charge radius, lattice dynamics, and fifth forces, Science 373**, 1239-1243 (2021).

P. Fierlinger et al., **Phys. Rev. Proposal for a Ramsey Neutron-Beam Experiment to Search for Ultralight Axion Dark Matter at the ESS,** Phys. Rev. Lett. 133, 181001 (2024).

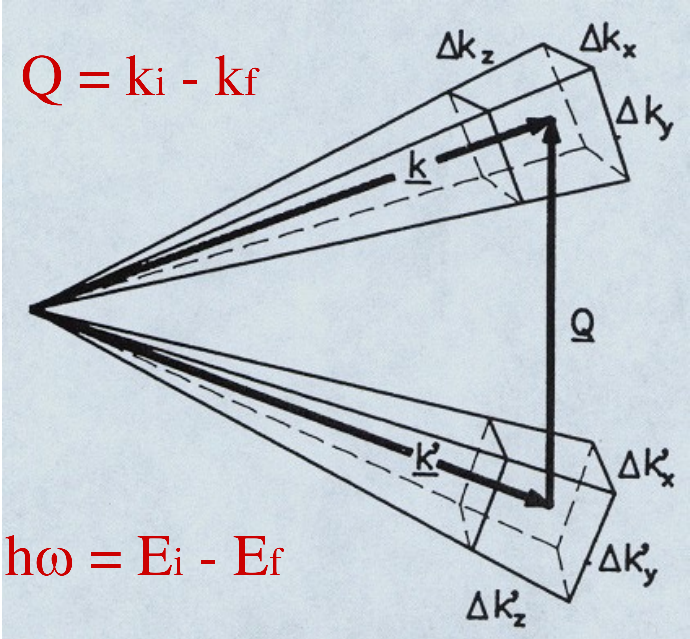
N. Geerits et al., **Measuring the Angular Momentum of a Neutron Using Earth's Rotation**, Phys. Rev. Res. **7**, 013046 (2025).

C. Hughes et al, **Polarized Neutron Images of a Ferrimagnet At T_{comp}**, Journal of Magnetism and Magnetic Materials **629**, 173273 (2025).

T. Mulkey et al., **Upper Bound on Exotic Polarized Neutron/Polarized Electron Interactions**, PRL **136**, 071801 (2026).

Slower Neutrons Can Probe Longer Length and Time Scales More Accurately

Theorem (Maier-Leibnitz, 1966): for scattering measurement at fixed ω, Q and fixed resolution δω/ω, δQ/Q, statistical accuracy on S(Q , ω) will increase as λ^2 if neutron scattering instrument can use all of the beam phase space

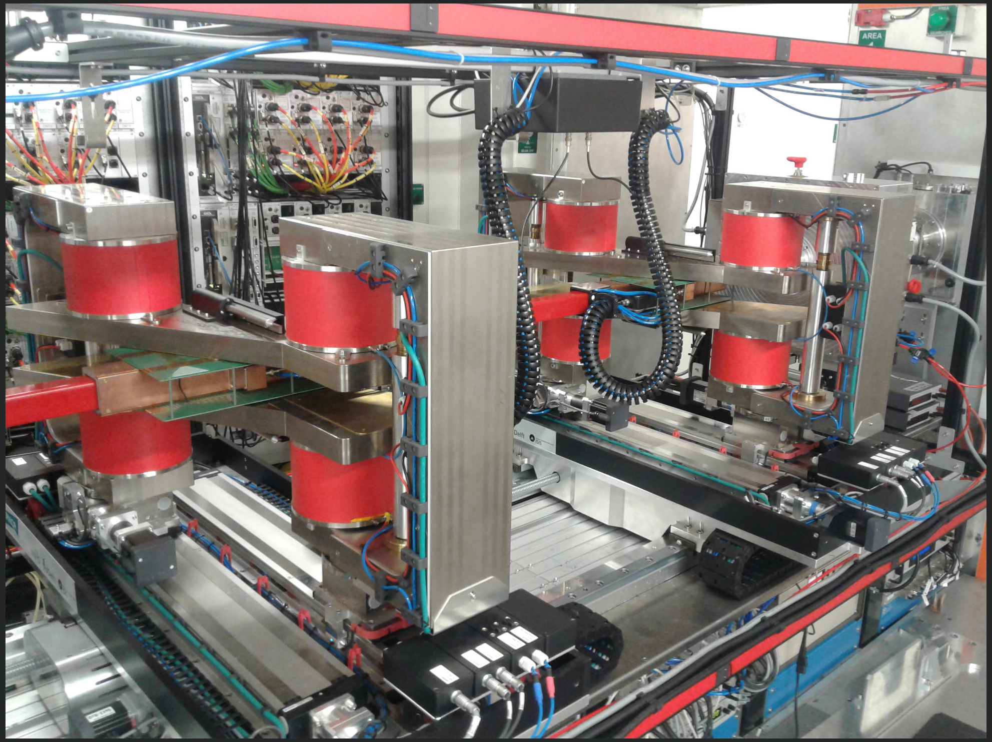


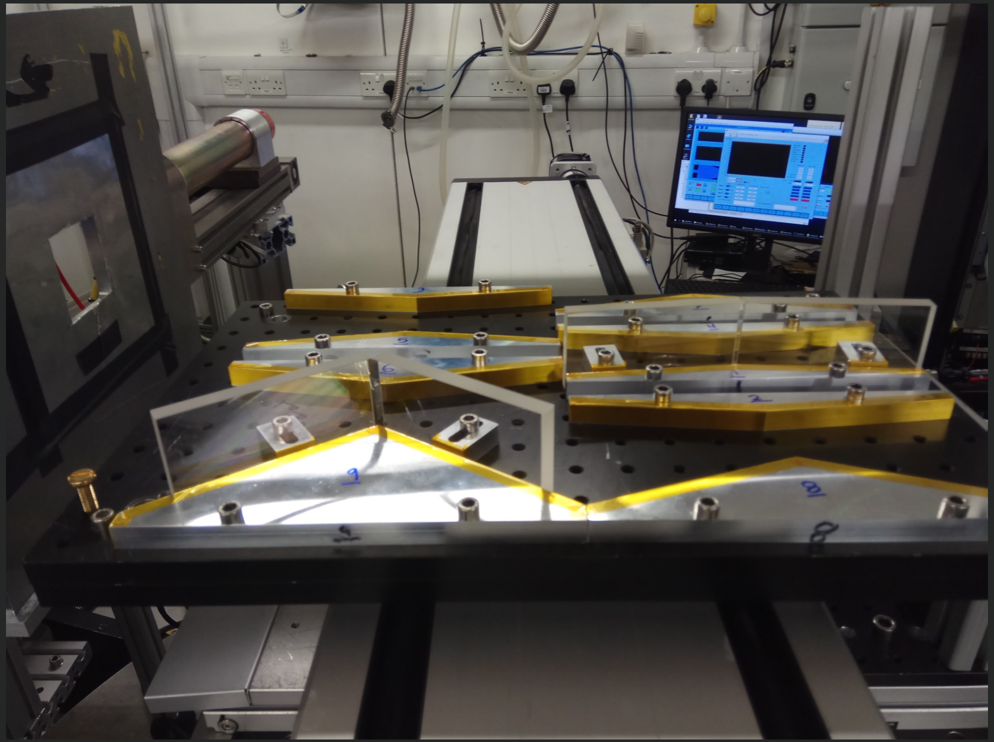
$$\frac{dN}{dx\,dy\,dz\,dk_x\,dk_y\,dk_z} \propto \phi_{th}\frac{1}{k_T^4}\exp[-\frac{k^2}{k_T^2}], \hbar k_T = \sqrt{2mk_BT}$$

Phase space density increases with colder source as $1/T^2$

Neutrons see conservative forces between cold source and instrument->phase space density is conserved (Liouville)

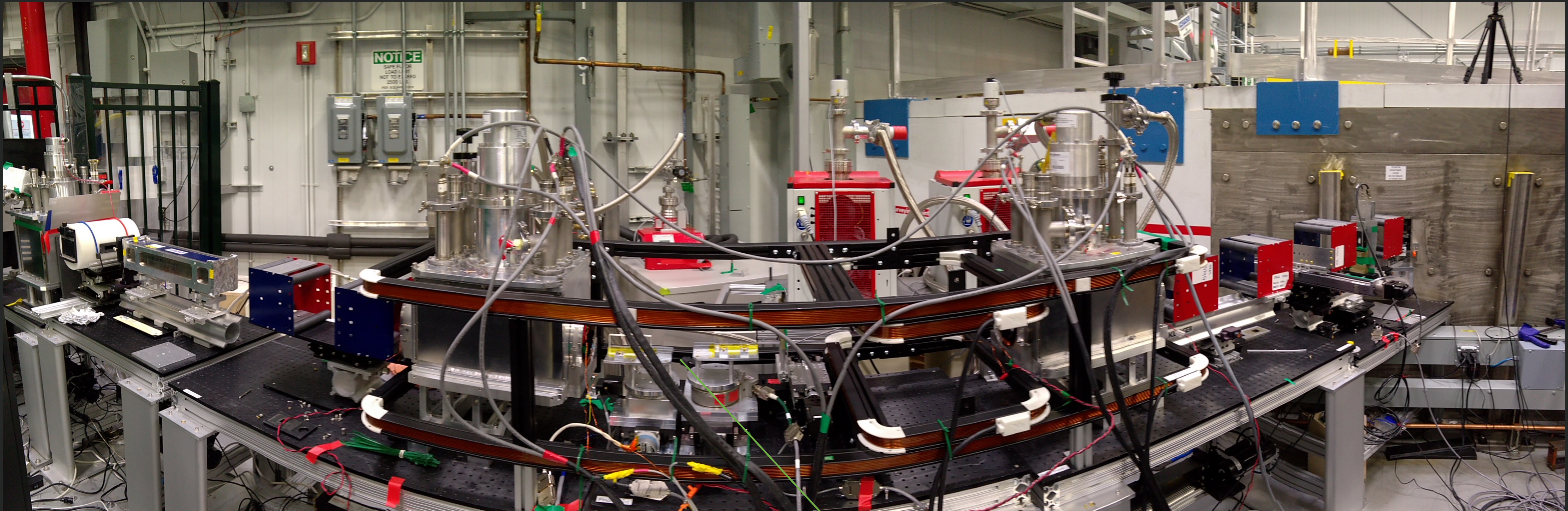
Pictures from the Larmor Neutron Spin Echo Spectrometer, ISIS

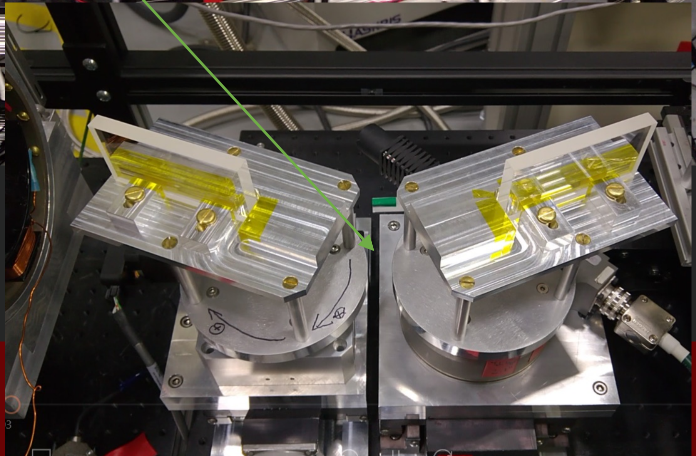




Left: Larmor RF flippers. Right: quartz block holder

Pictures from the HFIR Neutron Test Beam, ORNL





Up: HFIR apparatus setup

Right: HFIR quartz block holder