Neutron Quantum States as Probes of Gravity and New Interactions

Go Ichikawa (KEK)

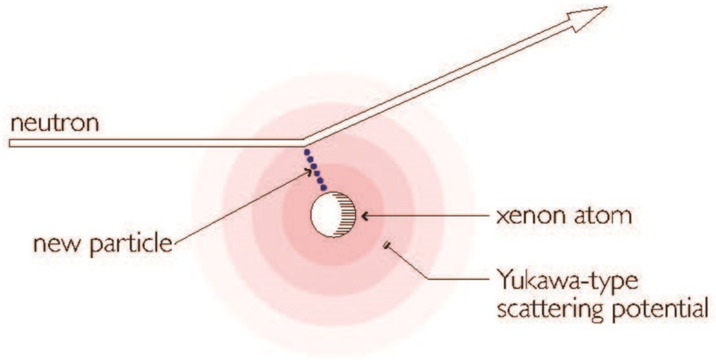
Oct. 28th, NEWS Colloquium, RCNP (zoom)

Introduction

Why neutrons?

- Neutrons have no net charge and a small electric polarizability, reducing electric backgrounds near surfaces.
- Small potentials can be probed through changes in neutron scattering, phase shifts, and quantum energy levels.
- Neutrons have a long lifetime (~880 s).

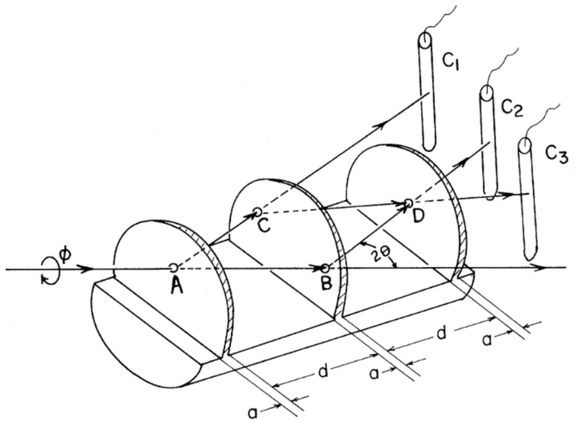
Neutron probes of gravity and new interactions



Scattering

→Angular distributions

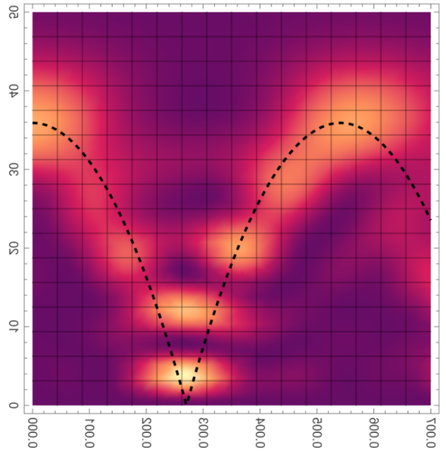
https://www.u-tokyo.ac.jp/focus/en/articles/a_00377.html



Interferometry

→Phase shifts

R. Colella, et al., PRL **34**, 1472 (1975).



Near-surface quantum states

→Energy levels and interference patterns

Low-energy probes of new physics

- Precision measurements at low energies complement collider and rare-process searches.
- New light bosons can mediate weak interactions between neutrons and matter.
- Such interactions can produce small shifts in quantum energy levels and interference patterns.

This talk explores neutron quantum states near material surfaces as probes of such interactions.

Short-range interactions with neutrons

A new boson coupled to neutrons and matter can mediate an additional interaction.

For single-boson exchange, the characteristic range is

$$\lambda = \frac{\hbar}{m_X c} .$$

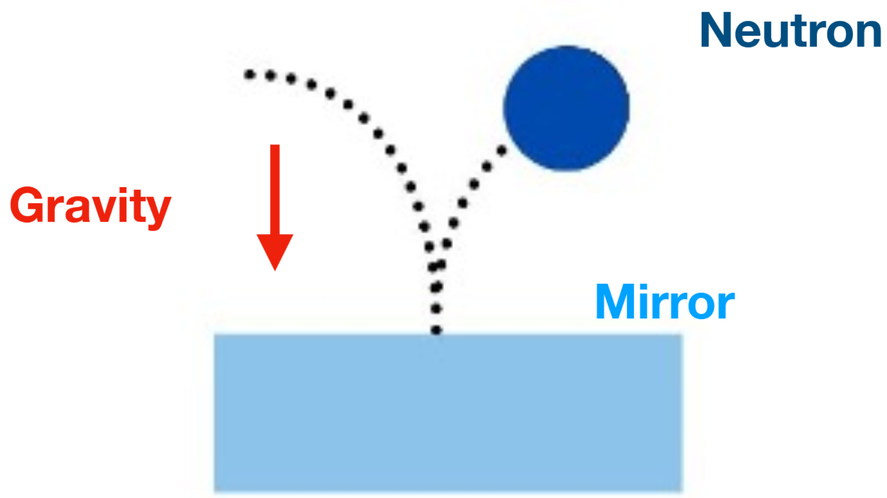
These interactions may depend on neutron spin and velocity.

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

Models of lepton-number breaking, relevant to neutrino masses and 0νββ, can introduce light bosons such as the Majoron and motivate searches for new interactions.

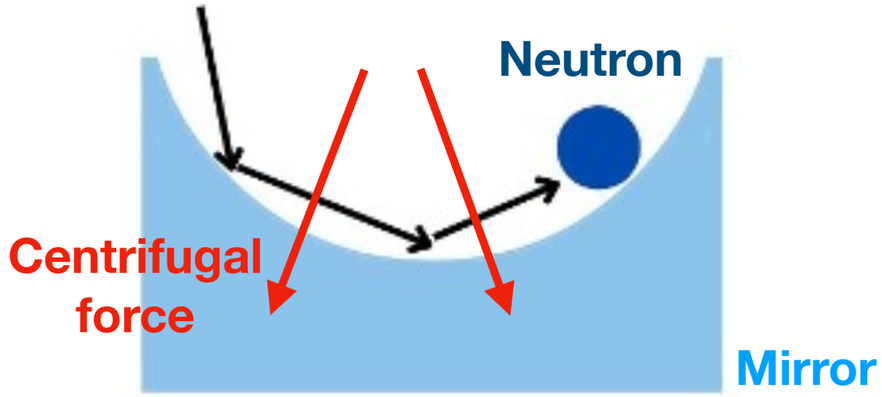
Near-surface quantum states

Neutrons are confined by a reflecting mirror and a linear potential.



Gravitational Quantum States (GQS)

gravity, micrometer scale



Neutron Whispering Gallery (NWG)

centrifugal acceleration, nanometer scale

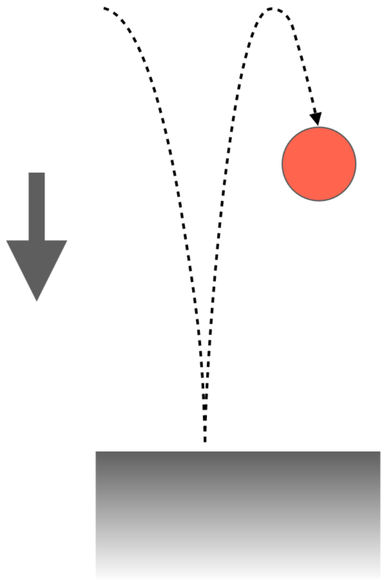
Additional interactions can shift the energy levels and interference patterns.

Gravitational Quantum States (GQS)

Measuring Gravity in Classical Mechanics

How do we measure gravity?

The simplest experiment is to drop an object and watch how it falls.



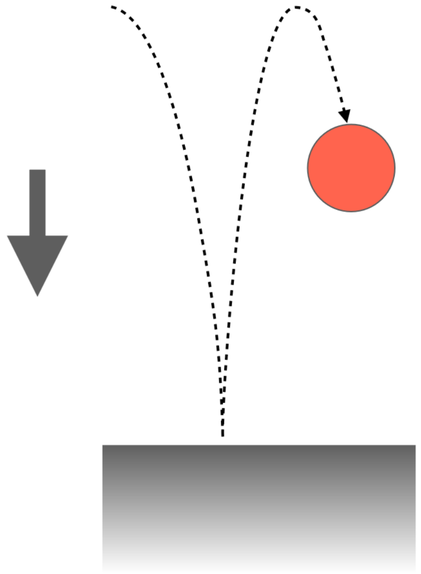
$$h = \frac{1}{2}gt^2 \quad \rightarrow \quad g = \frac{2h}{t^2}$$

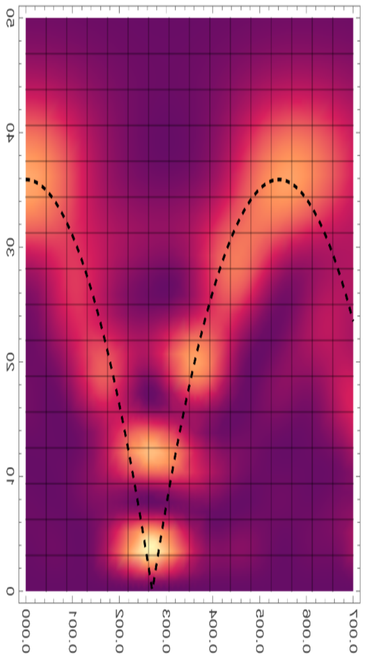


How about in quantum mechanics?

Gravity in Quantum Mechanics

But what happens if the falling object is not a classical ball, but a quantum particle?





Above a reflecting mirror,
the vertical motion becomes quantized.

We probe the quantum states through their spatial distributions and energy spacings.

Deviations from the predictions could reveal new physics.

Gravitational Quantum States of Neutrons

Gravitational quantum states have so far been observed only with neutrons.
The quantum bouncer is realized with ultracold neutrons (UCNs) and a material wall.

Schrödinger equation

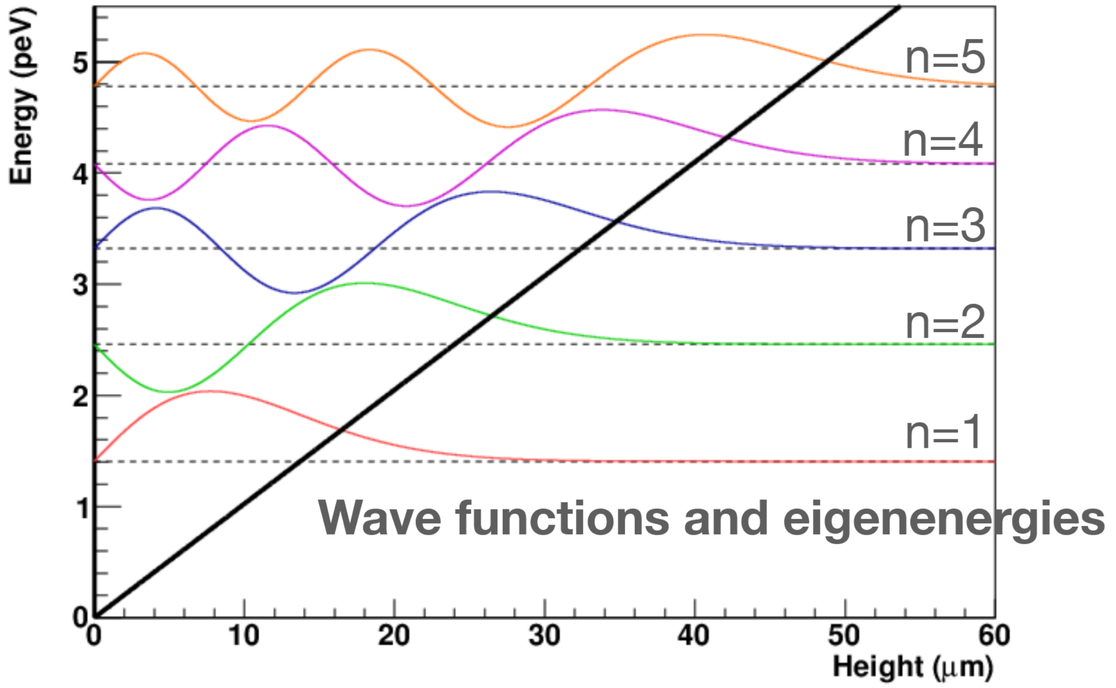
$$\left(-\frac{\hbar^2}{2m}\frac{\mathrm{d}^2}{\mathrm{d}z^2}+mgz\right)\psi(z)=E\psi(z) \qquad \begin{cases}\psi(0)=0\\ \lim_{z\to\infty}\psi(z)\to 0\end{cases}$$

$$\psi_n(z)=\frac{\mathrm{Ai}(z/z_0+\lambda_n)}{\sqrt{z_0}\,\mathrm{Ai}'(\lambda_n)} \qquad z_0=\left(\frac{\hbar^2}{2m^2g}\right)^{1/3}=5.869\,\mu\mathrm{m}$$

Ai: Airy function

λ_n: n-th zero of Ai

$$E_0=mgz_0=0.6016\,\mathrm{peV}$$



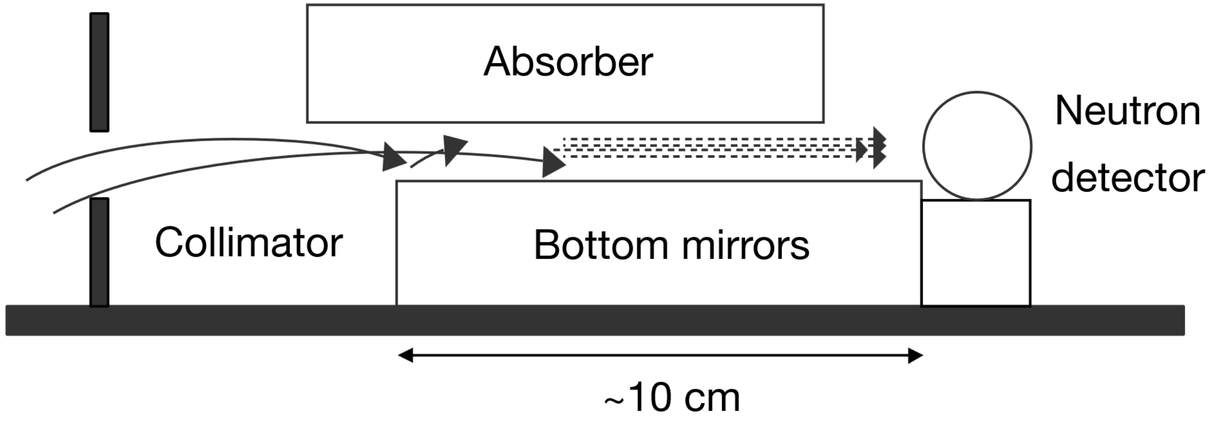
The ground state has $E_1=1.41\,\mathrm{peV}$ and $z_1=13.7$ μm.

Integral Measurement (First Observation)

The ground state was observed by ILL-group with the integral measurement.

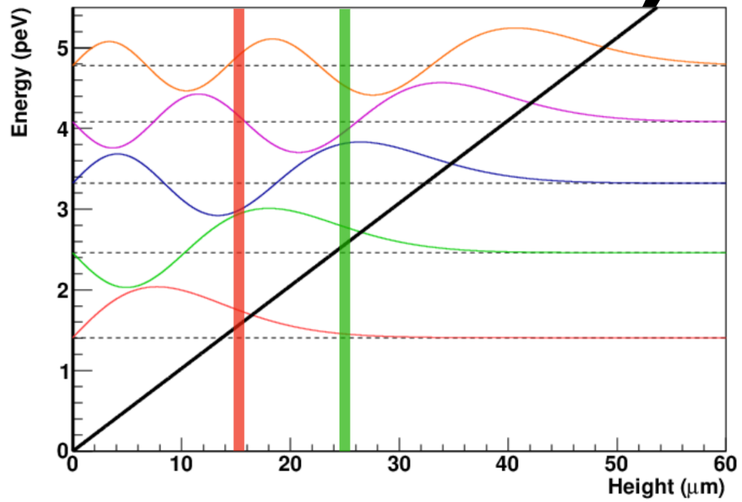
The absorber removes higher gravitational states.

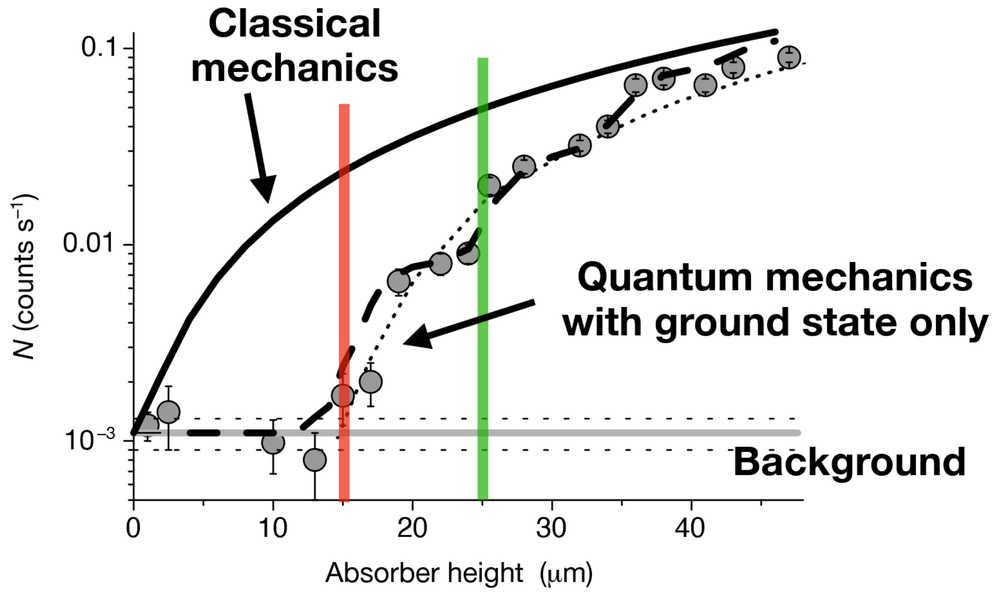
Nesvizhevsky et al., Nature **415**, 297 (2002)



By changing the absorber height, they observed that neutron transmission was strongly suppressed for < 15 μm.

The discovery of the ground state



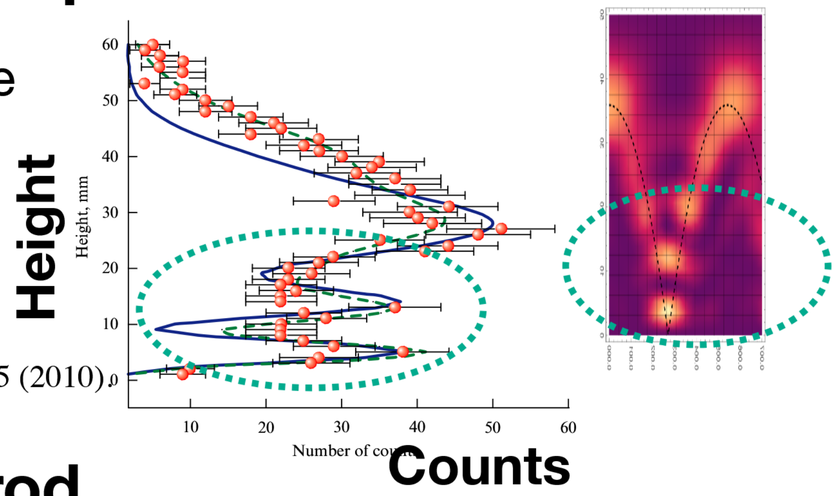


Integral measurement achieved characteristic scale $\delta z_0/z_0$ ~ 10%.

Spatial Measurement

Detector with >1 μm resolution

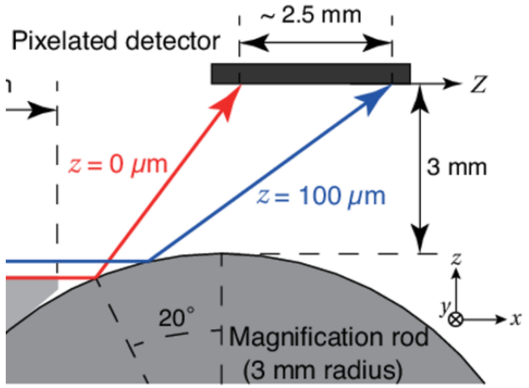
Using a step to make fine structures.
(1-2 μm resolution)



Nesvizhevsky et al., Phys.-Usp. **53**, 645 (2010).

Magnification rod

Collaborators at Komamiya-lab of the Univ. Tokyo.

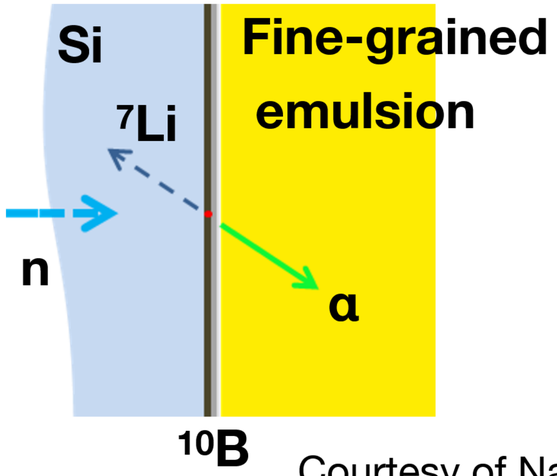


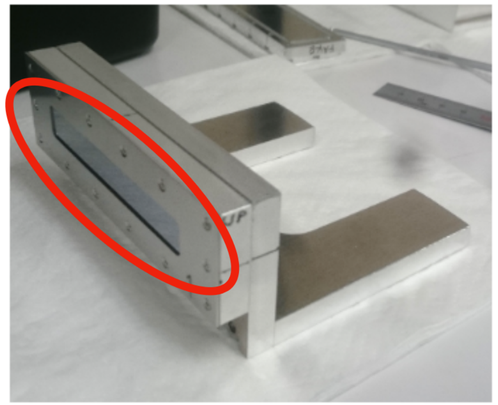
Corresponds to ~ 0.7 μm

Ichikawa et al., PRL **112**, 071101 (2014).

Sub-micron resolution detector

Detector with nuclear emulsion for UCNs.





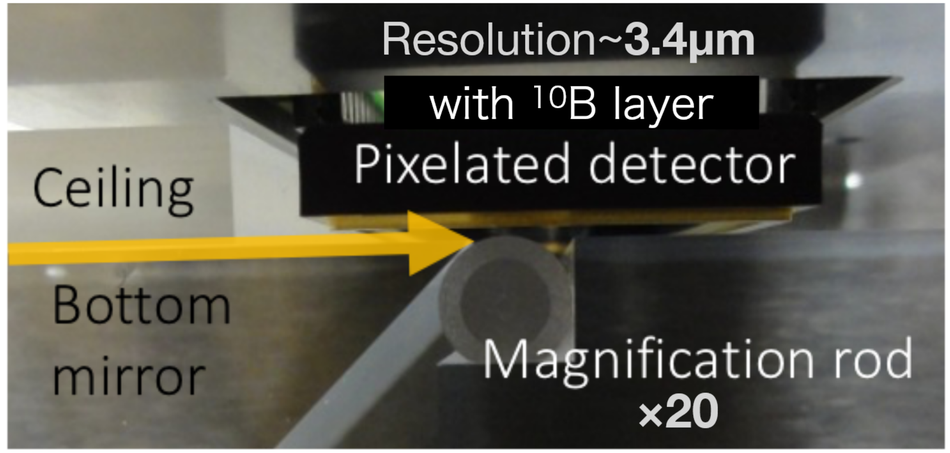
Courtesy of Naganawa-san (Nagoya Univ.)

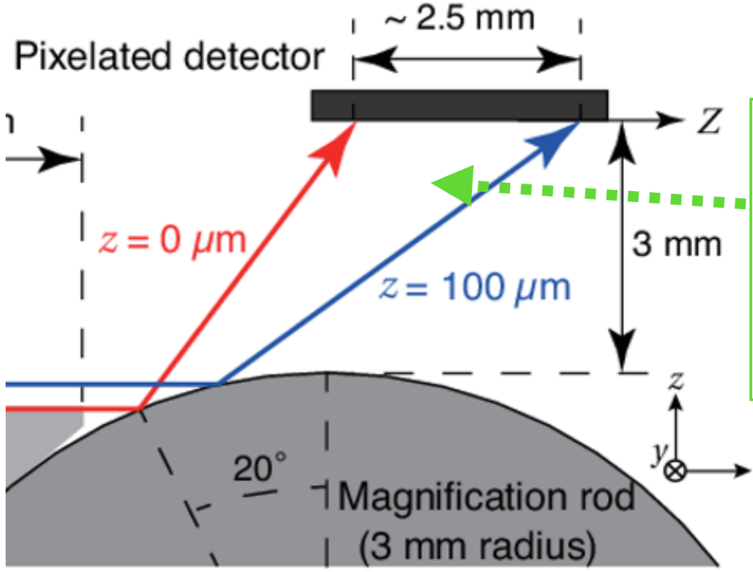
Inclusive resolution < 1 μm.
Detector resolution < 0.1 μm

Naganawa et al., EPJC **78**, 959 (2018).

Spatial Magnification of Quantum States (Tokyo)

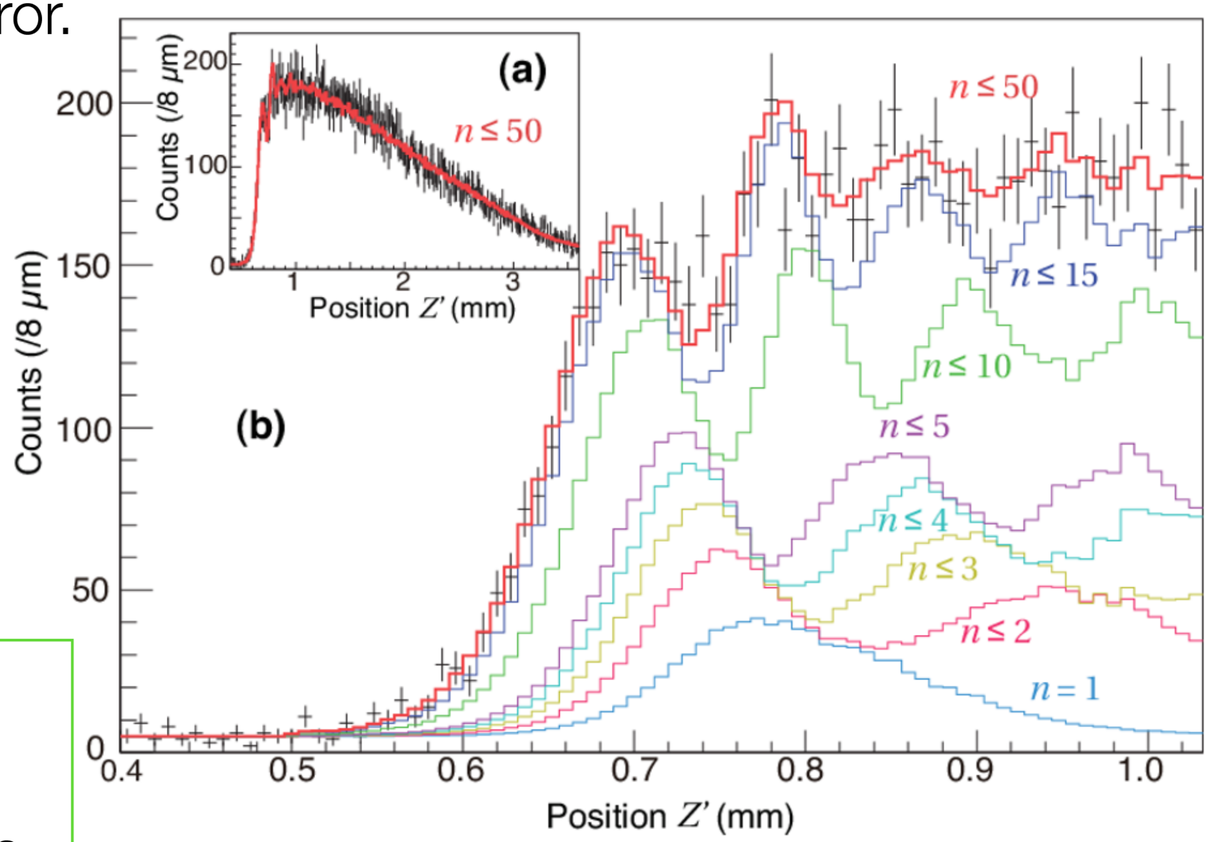
Magnifying the neutron image by a convex mirror.





Dispersion is calculated by using the phase space of quantum mechanics. (Wigner function)

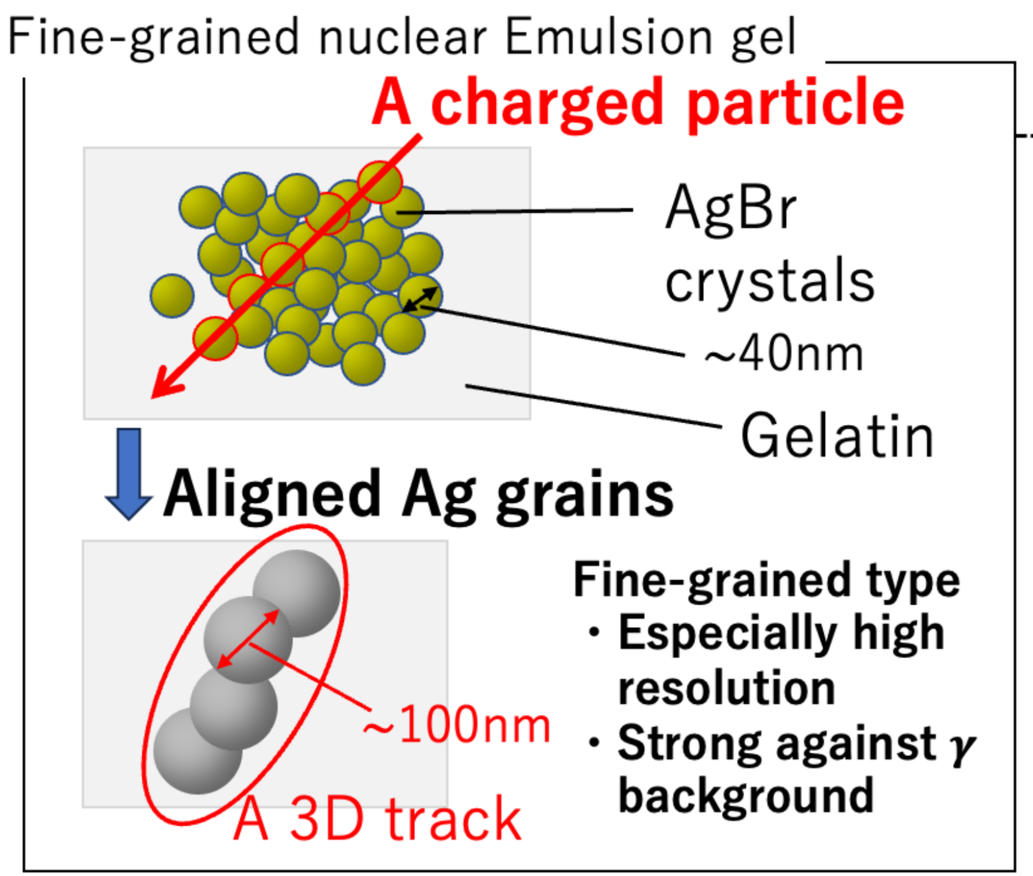
GI, et al., Phys. Rev. Lett. 112 071101 (2014).



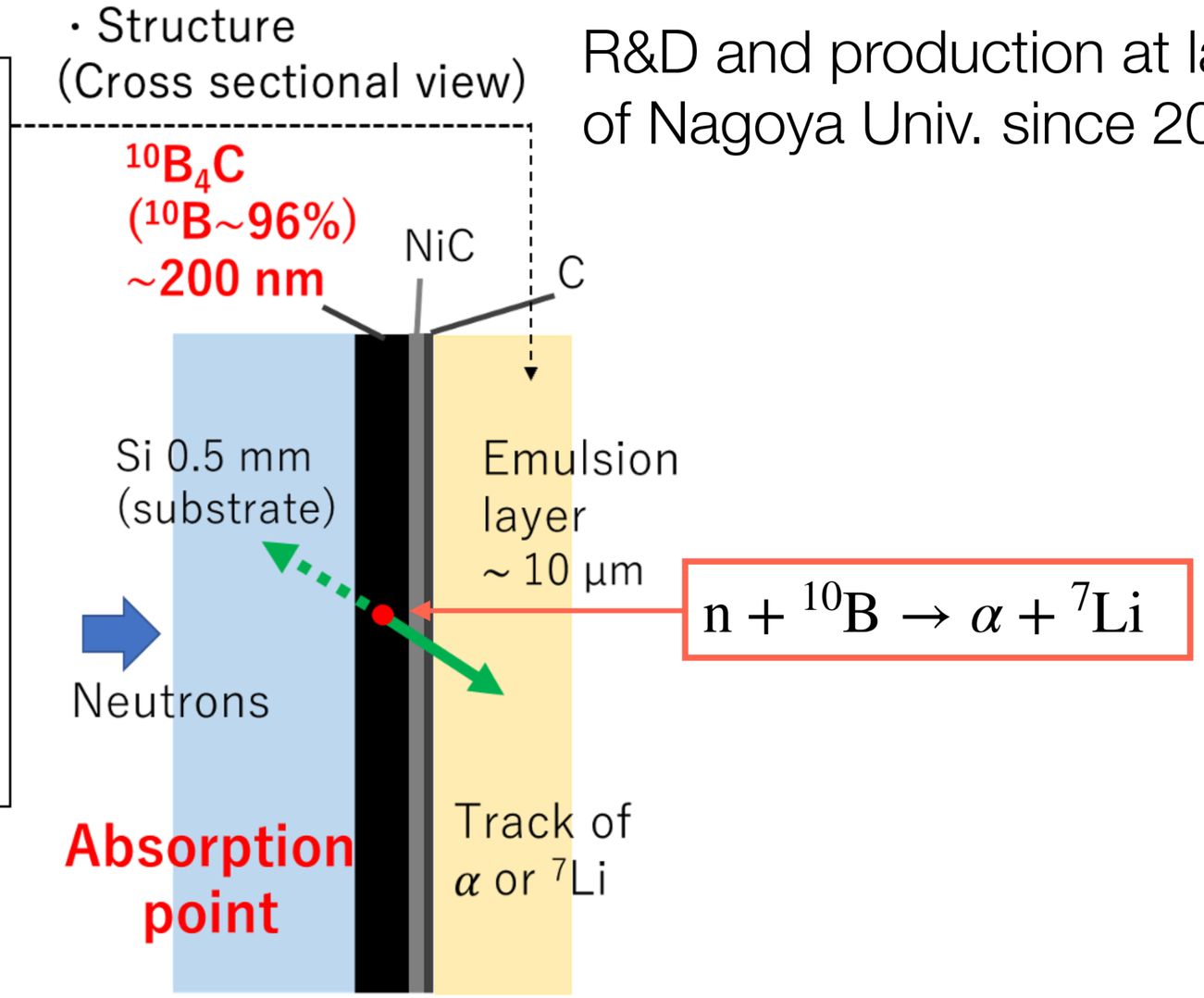
Resolution is equivalent to **0.7 μm**, but the systematic error disturbs the search for short-range gravity.

→ Our group has developed a detector with sub-micron resolution without magnification.

Neutron Detector using Fine-Grained Emulsion



Resolution < 100 nm
($\theta \leq 0.9$ rad)
(linear fitting and Extrapolation of tracks to $^{10}B_4C$ layer)

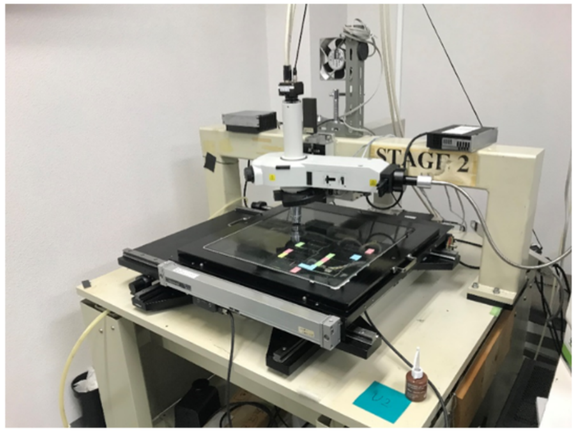


R&D and production at lab-F of Nagoya Univ. since 2010.

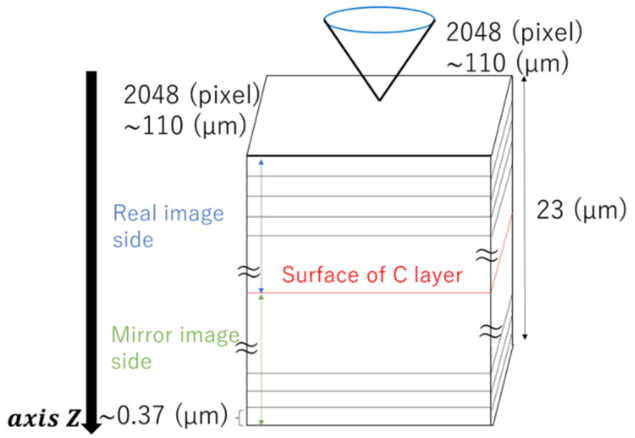
By courtesy of Naoto Muto

Track analysis and coordinate reconstruction

Automatic scanning system (PTS2)

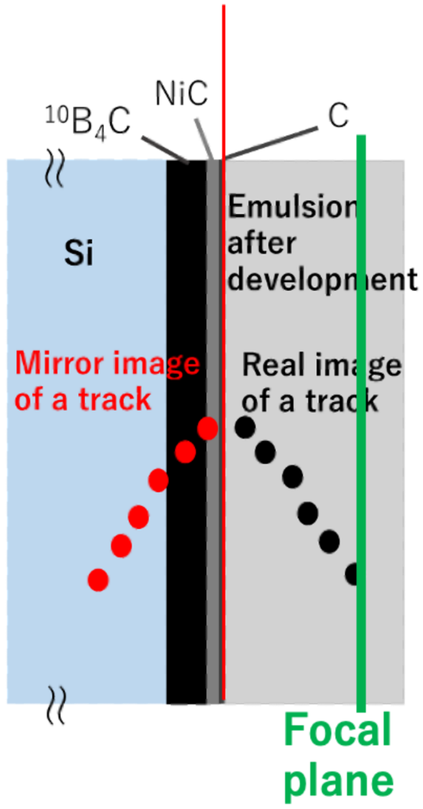


Objective lens



1~2 s/view(=(110μm)²)

C layer is mirror-like



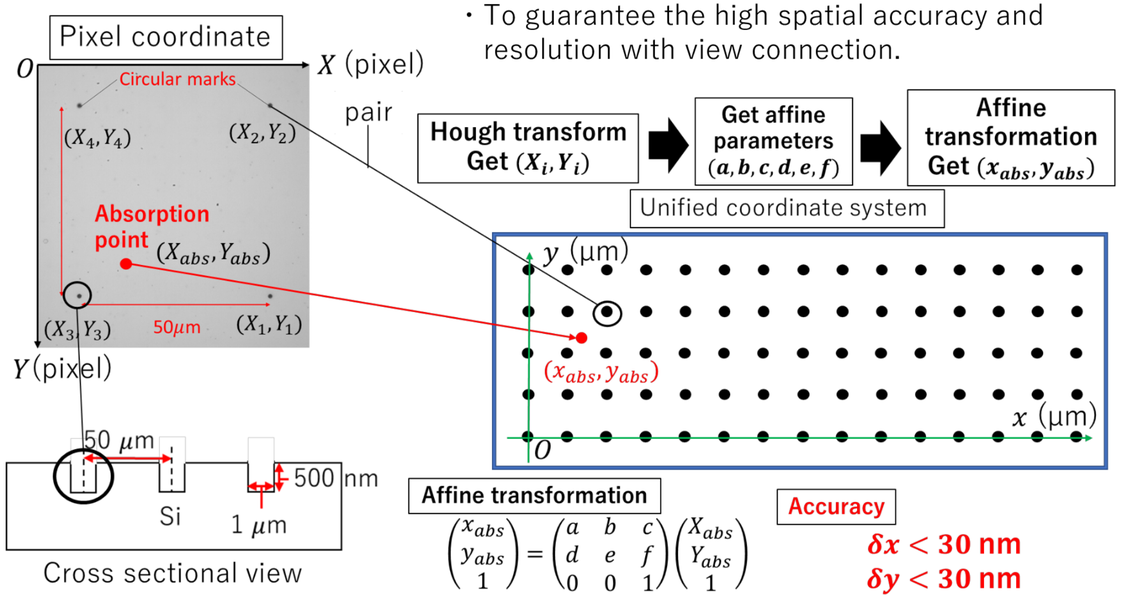
N. Naganawa, et al., Eur. Phys. J. C (2018) 78:959.
N. Muto, et al., 2022 JINST 17 P07014.

Reference marks

・Reference marks were formed by the electron beam lithography(EBL) method.

Purpose

・To guarantee the high spatial accuracy and resolution with view connection.



Affine transformation

$$\begin{pmatrix} x_{abs} \\ y_{abs} \\ 1 \end{pmatrix} = \begin{pmatrix} a & b & c \\ d & e & f \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} X_{abs} \\ Y_{abs} \\ 1 \end{pmatrix}$$

Accuracy

$\delta x < 30$ nm
$\delta y < 30$ nm

Achieved **< 100 nm** resolution by using track analysis.

Coordinate on the detector surface is reconstructed by using reference masks.

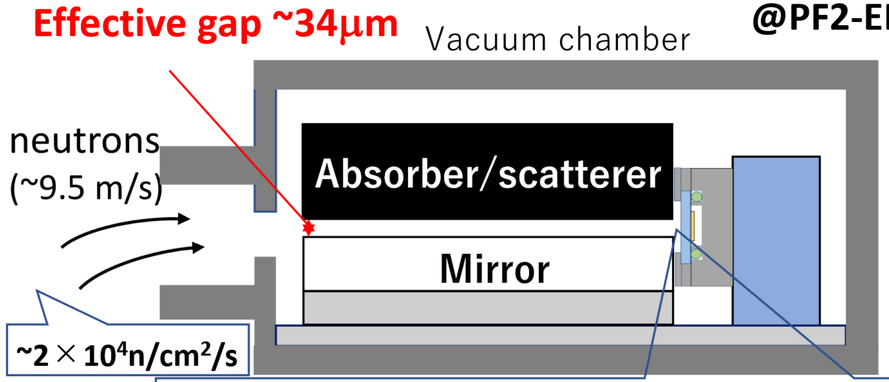
By courtesy of Naotaka Naganawa and Naoto Muto.

Measurement at ILL using qBOUNCE setup

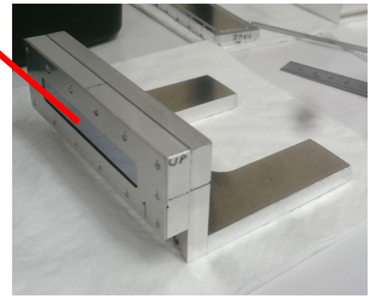
Test exposure to obtain the distribution of quantum states of UCNs

Effective gap ~34μm

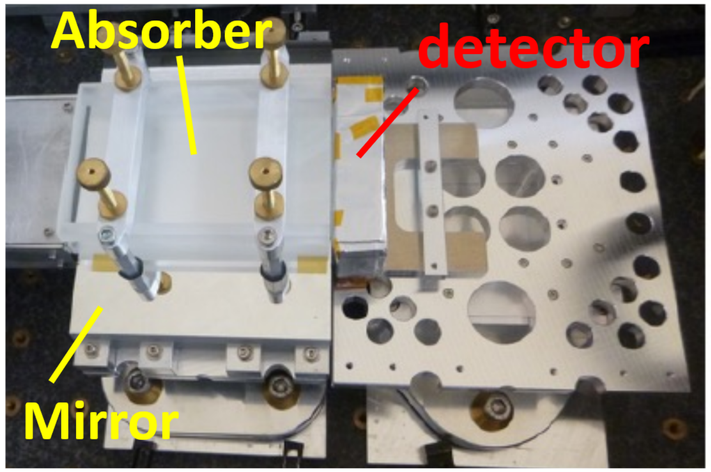
@PF2-EDM, Institut Laue-Langevin (2021)



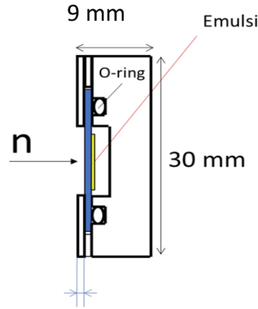
- Upstream surface of detector polished to **~0.5 nm**



0.10 n/s × 31 hours, 1.1 × 10⁴ n on detector
→~ 4600 int→~ 1800 events for analysis ($\theta \leq 0.9$)



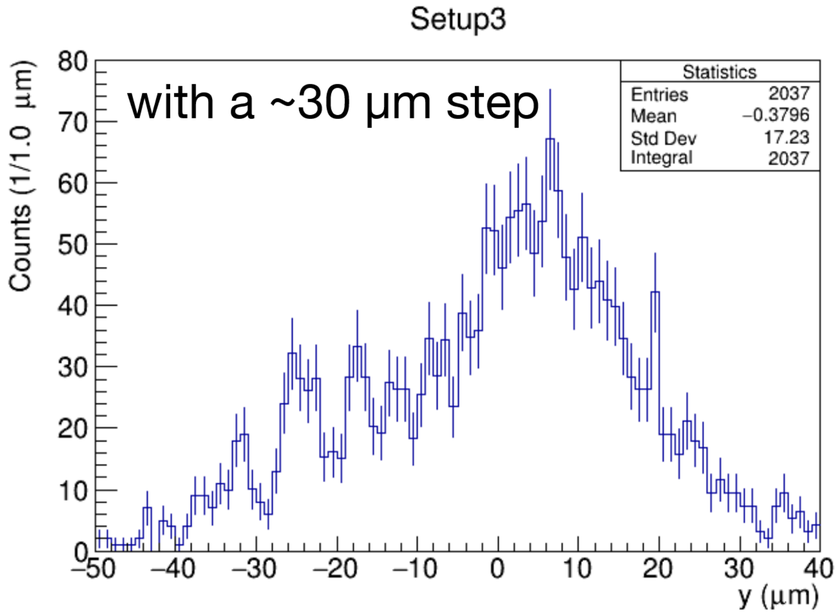
Mirror, absorber, supports, and vacuum chamber of the qBOUNCE collaboration



- Lid of the holder 0.5 mm (Neutron flight length 1.0 mm)

- Due to covid-19's situation, the detector was sent to the ILL → exposed → sent back to Nagoya → developed → Analyzed.

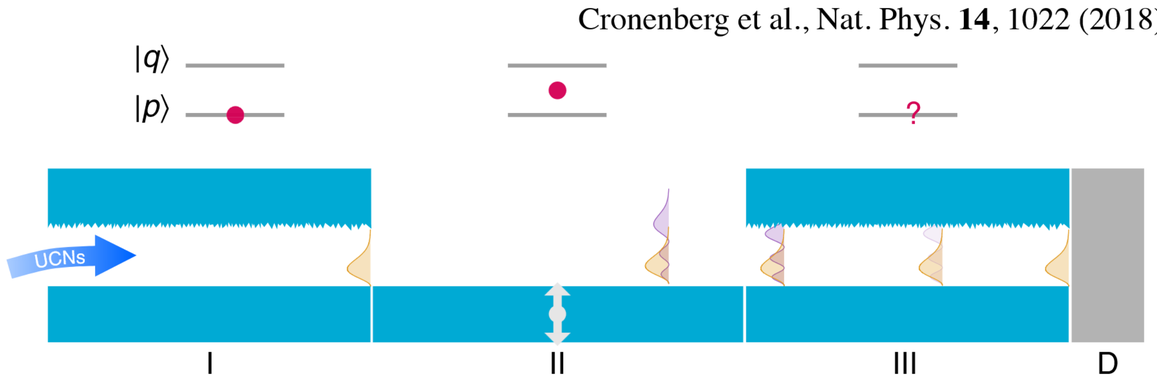
We measured the gravitationally bound states at ILL (Institute Laue-Langevin).
A holder for using inside the vacuum chamber was developed.



By courtesy of Naotaka Naganawa

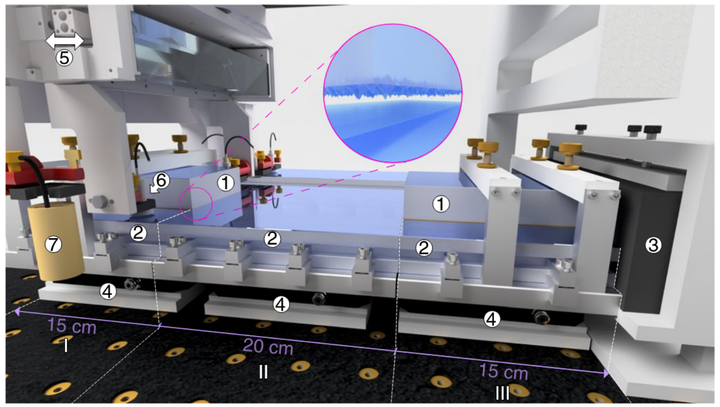
Spectroscopic Measurement (qBOUNCE)

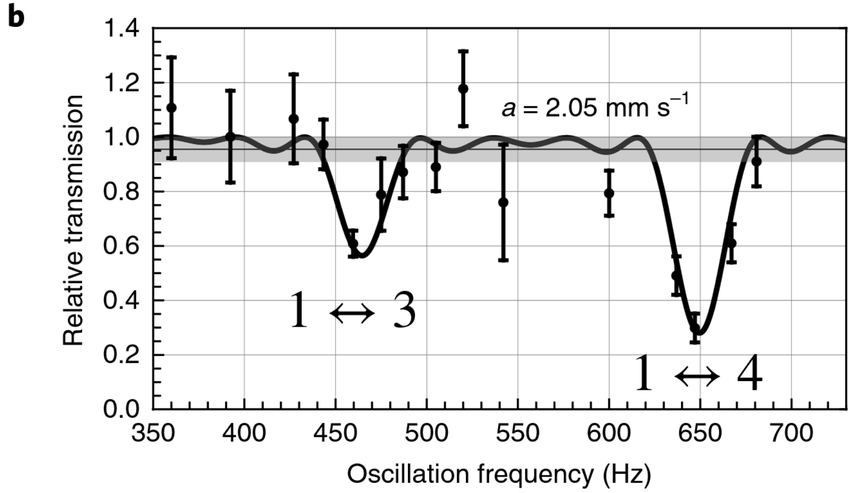
Spectroscopy with Rabi oscillation



I. Make ground state UCNs
II. Vibrate the mirror
III. Count UCNs with the selector

If transition occurs, the count reduced.





They also realized Ramsey method and achieved $\delta g/g \sim 10^{-4}$ (stat.).

J. Micko, Ph.D. thesis, TU Wien (2023).

There is discrepancy between g of qBOUNCE and classical method by 2-4σ.

F. Lachaume, Ph.D. thesis, TU Wien (2026).

Constraints on New Physics

Measurement of gravitational quantum states can constrain additional interactions.

$$V(z) = mgz + \delta V(z)$$

New physics

Screened scalar fields (Dark energy)

Chameleon / Symmetron

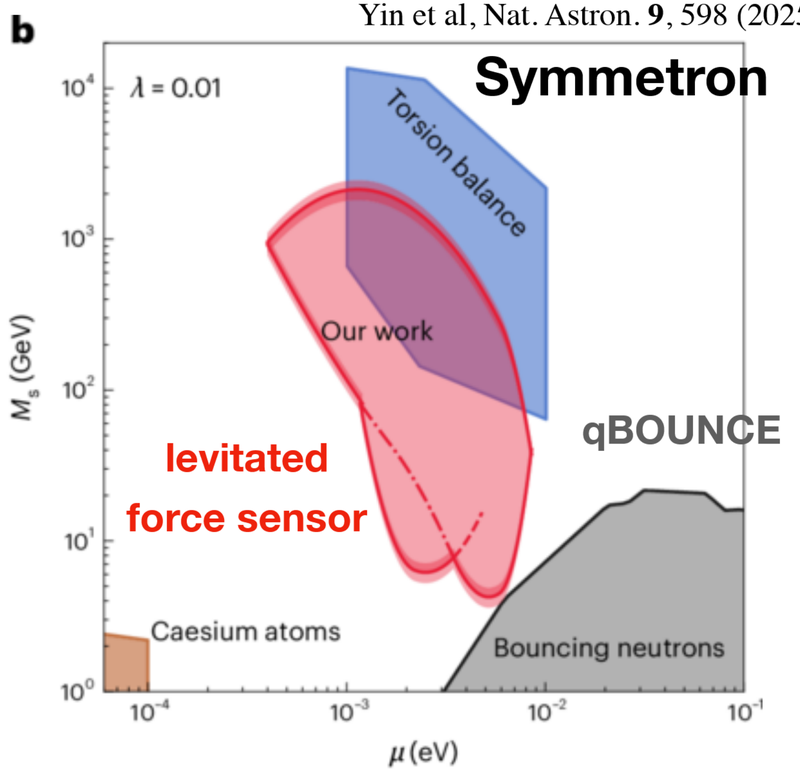
Axion-like particles

Spin-independent short-range interactions

Spin-dependent short-range interactions

Lorentz violation

Yin et al, Nat. Astron. **9**, 598 (2025).



Neutron Whispering Gallery (NWG)

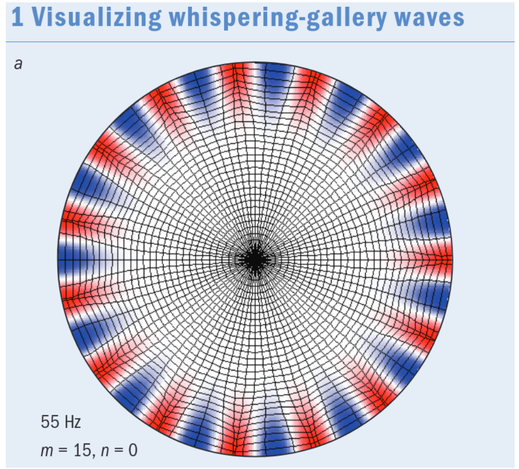
What is neutron whispering gallery?



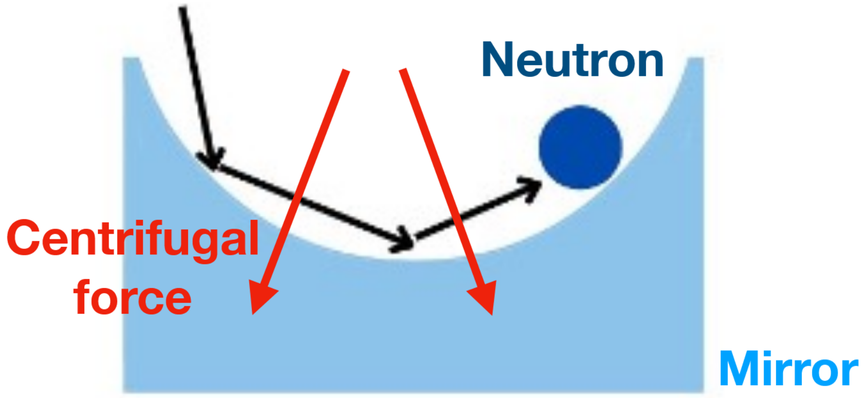
In the whispering gallery of St. Paul's Cathedral, you can hear a whisper from the opposite side.

Photo by Femtoquake, CC BY-SA 3.0
https://commons.wikimedia.org/wiki/File:St_Paul%27s_Cathedral_Whispering_Gallery.jpg

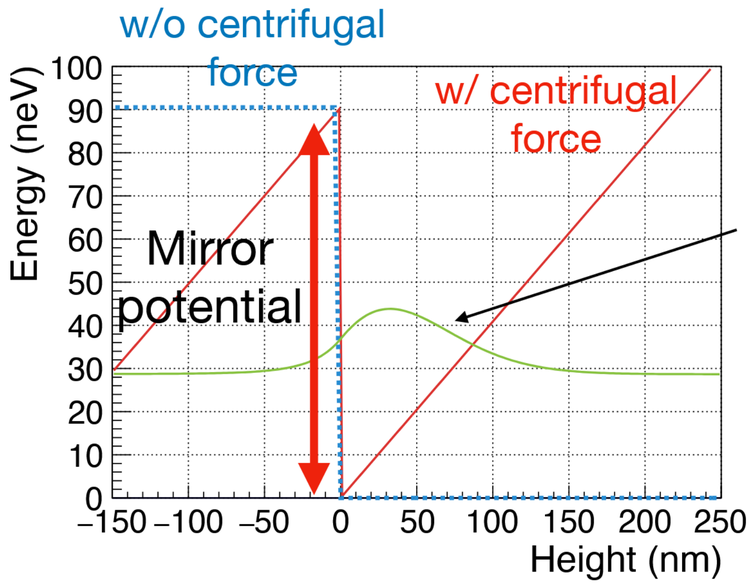
O. Wright 2012 Phys. World **25** (02) 31.



Lord Rayleigh discovered that the phenomenon was due to standing waves (whispering gallery mode).



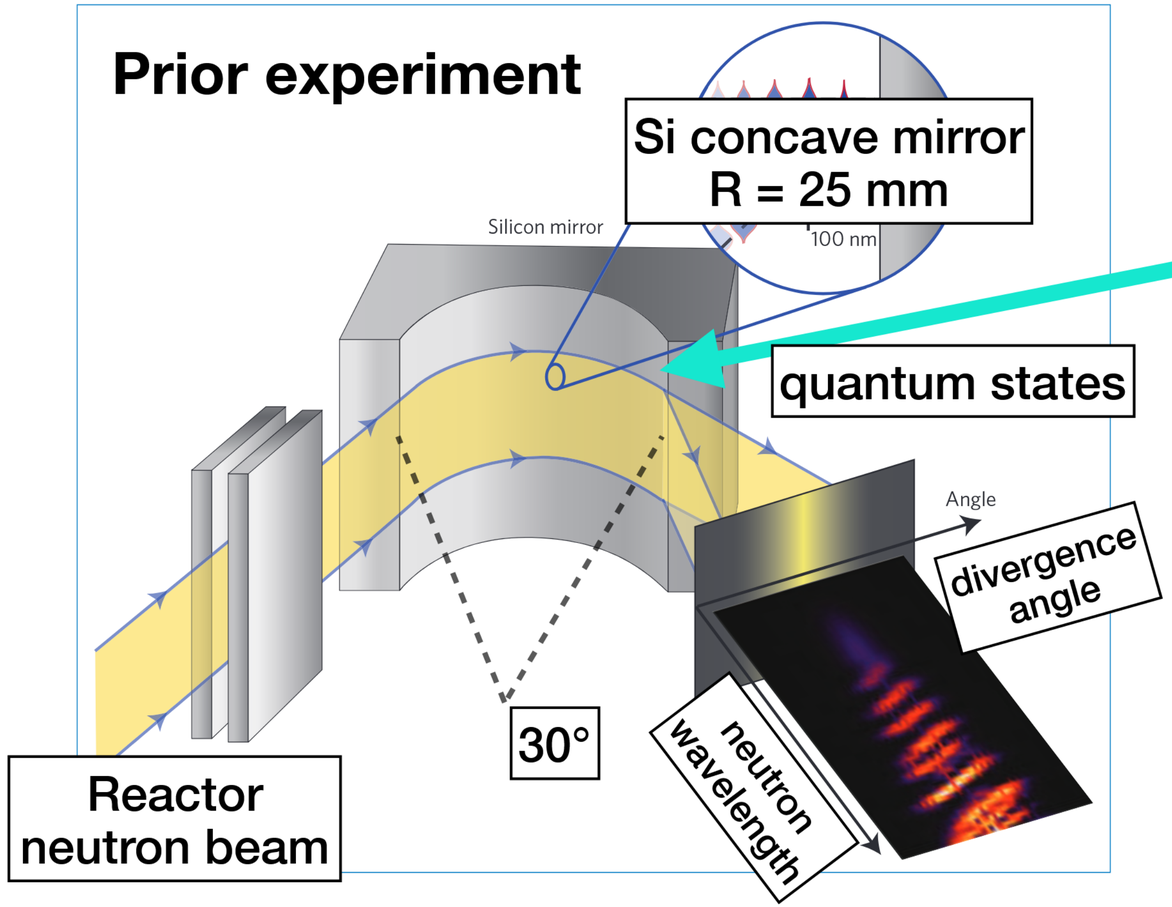
A neutron whispering gallery can be created using a cold neutron beam and a concave mirror.



The quantum state of a neutron whispering gallery is confined between a mirror and the centrifugal force.

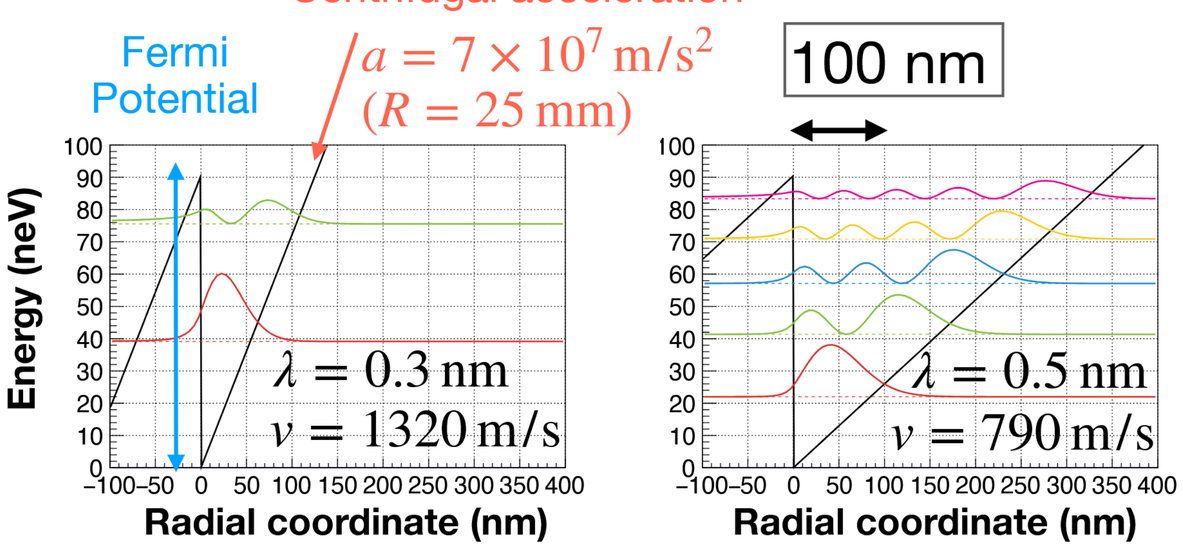
Neutron whispering gallery experiment

V. V. Nesvizhevsky, et al., Nature Phys. 6 (2010) 114-117.



H. Rauch, Nature Phys. 6 (2010) 79.

At ILL reactor PF1B D17 (reflectometer).
peak: λ=5 Å



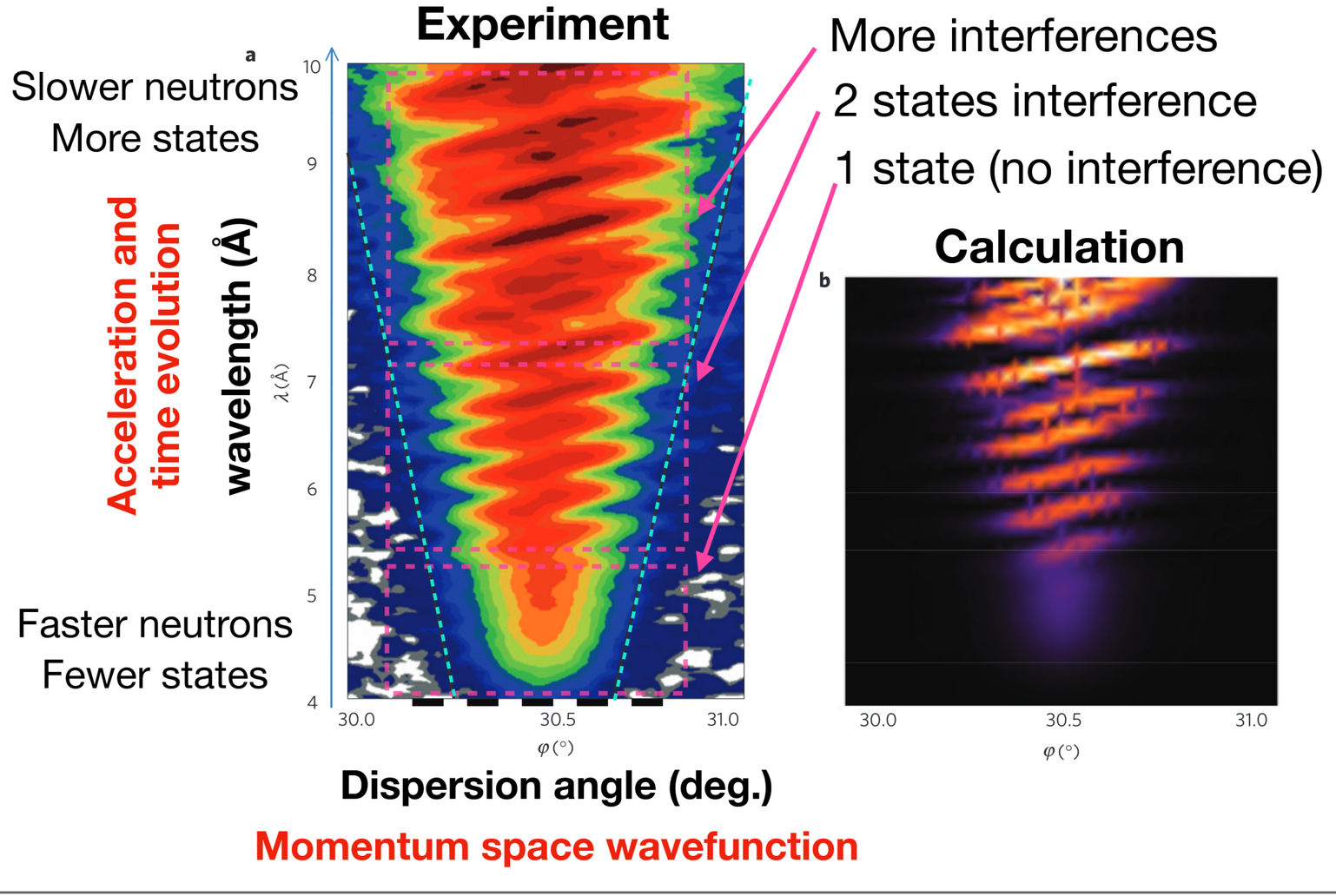
- faster neutrons
- Steep potential slope
- fewer states survive

- slower neutrons
- gentle potential slope
- more states survive

The hypothetical interactions between neutrons and the mirror can be studied.

Discovery of neutron whispering gallery

V. V. Nesvizhevsky, et al., Nature Phys. 6 (2010) 114-117.



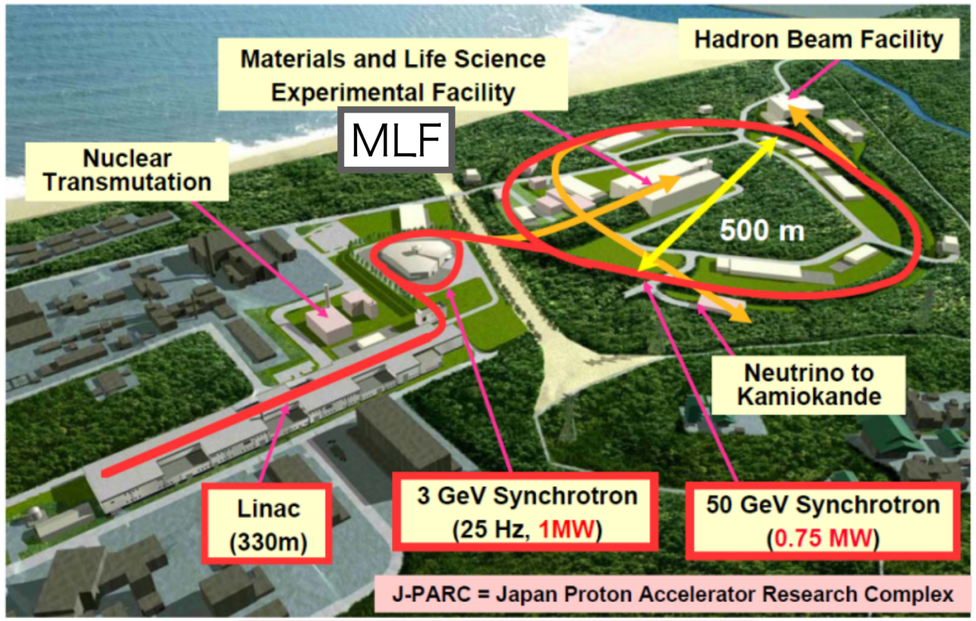
The interference fringe wavelength of the two lowest states is defined by $(E_2 - E_1)t/\hbar$. Therefore, we can measure the energy difference.

The quantitative results were not achieved due to the surface oxidation of the Si surface.

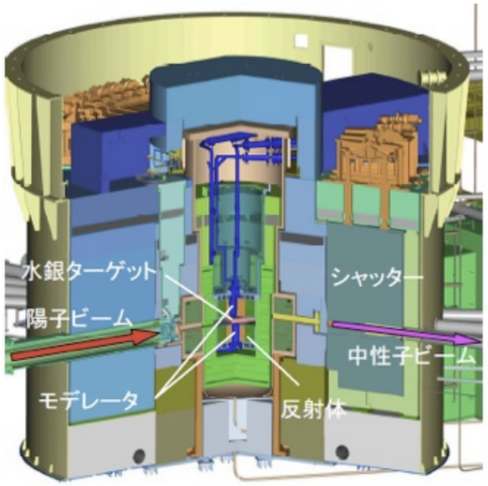
Our experiment at J-PARC

- **40 times neutron intensity**
- **Highly polished SiO_2 mirror**

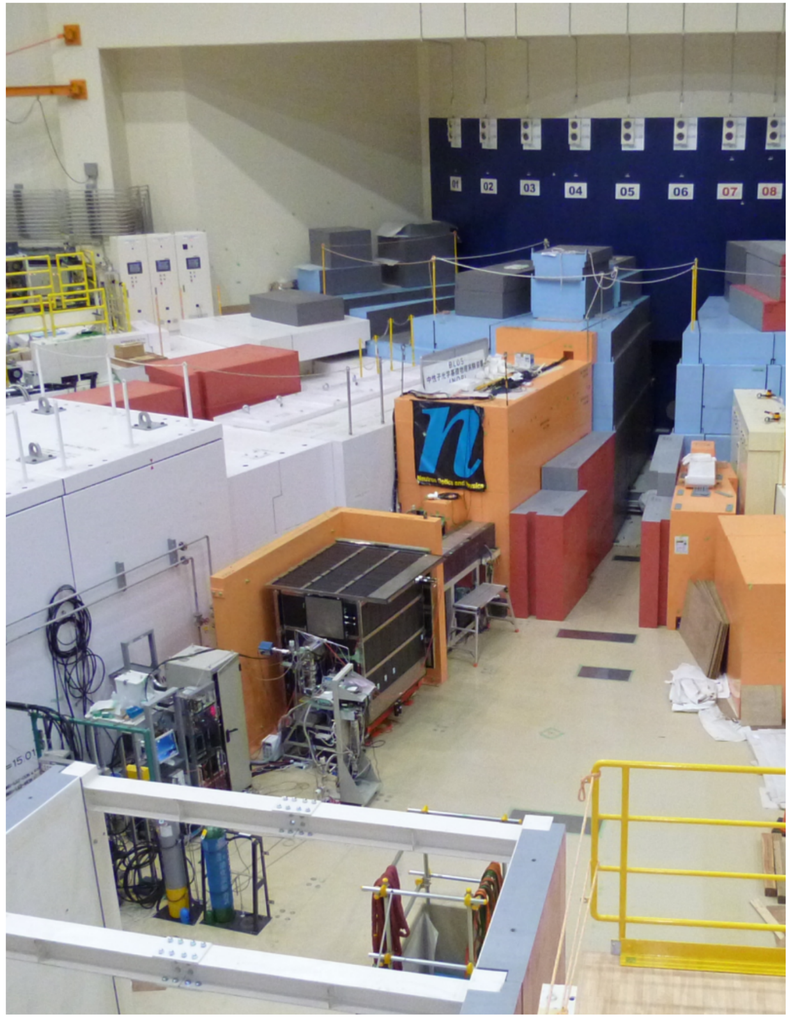
J-PARC MLF BL05



Joint Project between KEK and JAEA



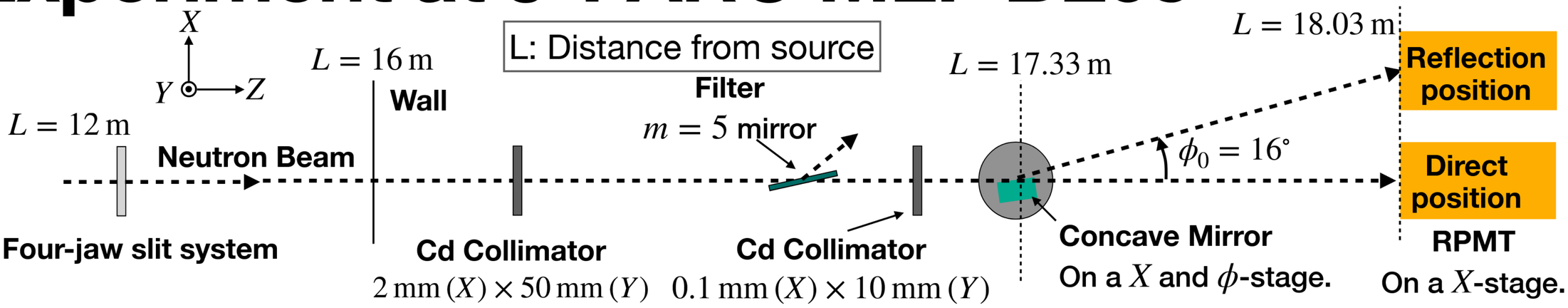
A 3 GeV proton beam is incident on a mercury target at 25 Hz, producing spallation neutrons that are slowed in a moderator to form a cold neutron beam.

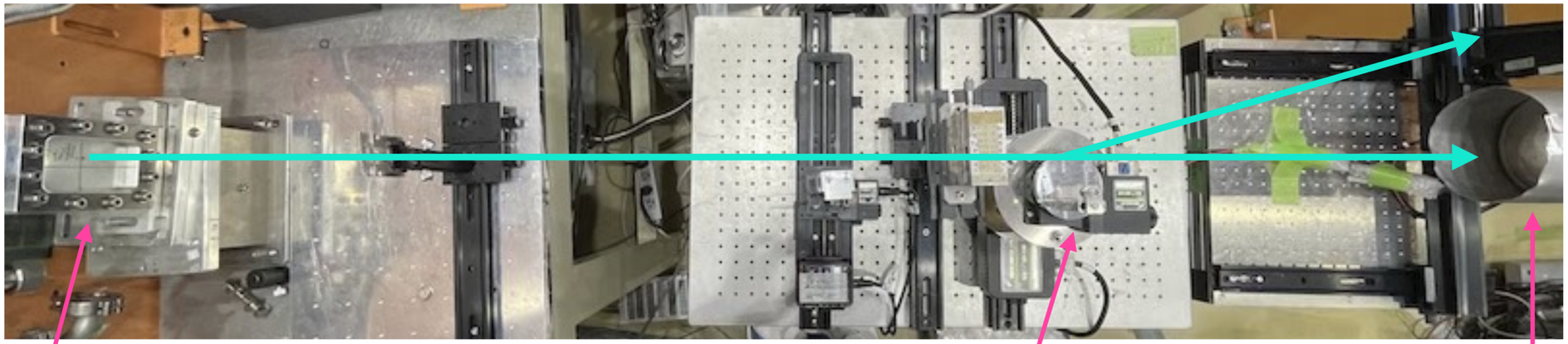


BL05 (NOP)

Experiment at J-PARC MLF BL05

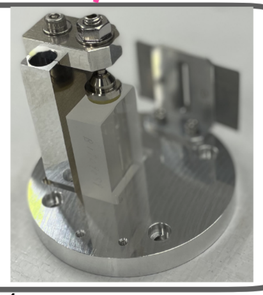
Phys. Rev. D 111, 082008 (2025).





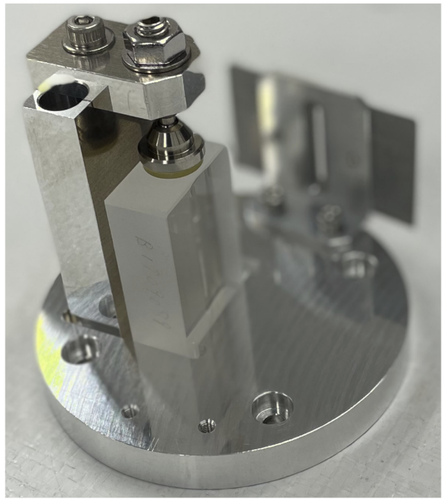
BL05 Low div. branch
MLF cycle: 25 Hz
Horizontal div.
σ_H=0.090 mrad.

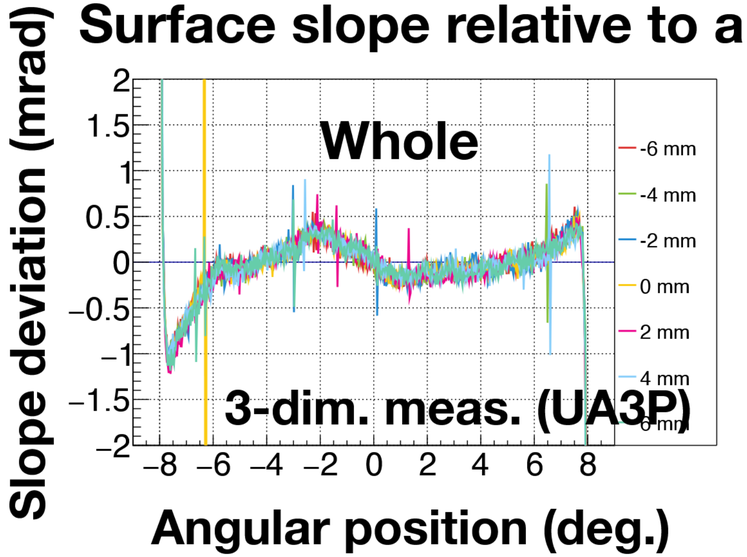
Concave mirror (Crystal optics)
15×25×40, R=25, ϕ_0=16°
Roughness Ra=0.58 nm
(0.08×0.08 mm^2)



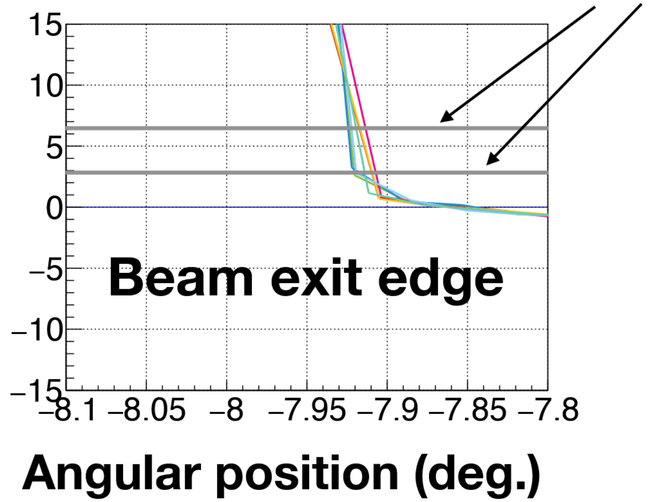
RPMT detector
ZnS(Ag)/^{6}LiF
σ=0.1 mm with time resolution
detection radius < 25 mm

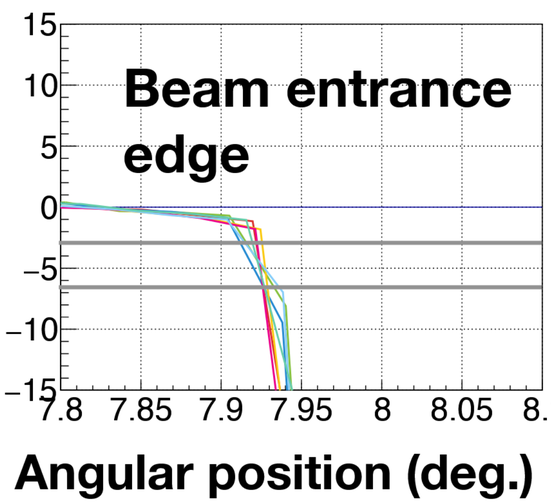
Surface profile of the concave mirror





Used to determine the angular span.





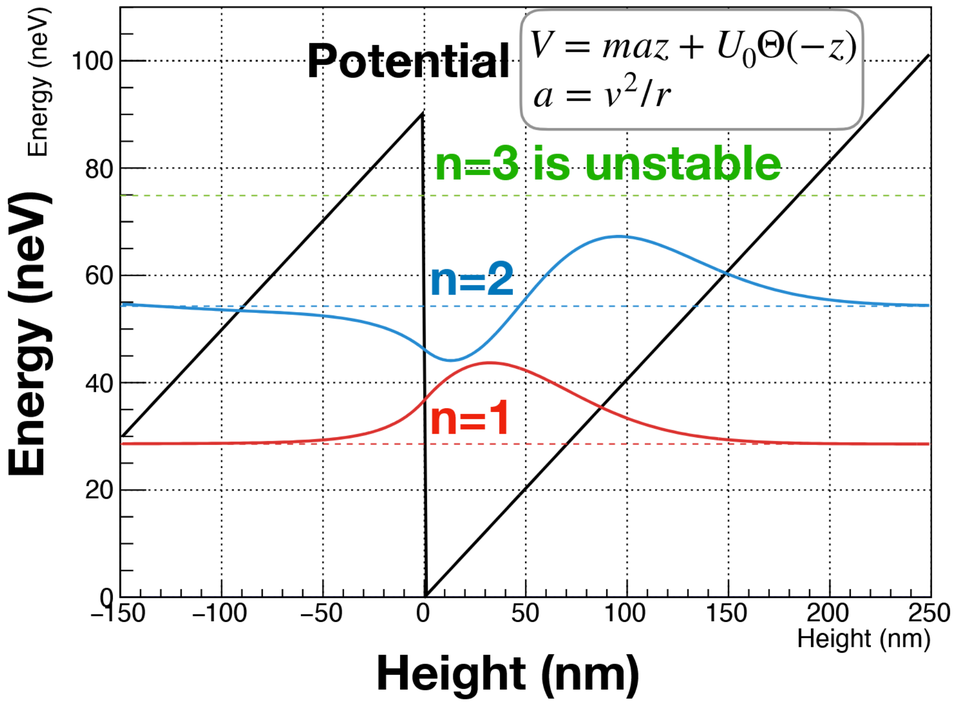
The angular span was determined by these angles.

$$\phi_0^{\mathrm{surf}} = 15.86(2)^\circ$$

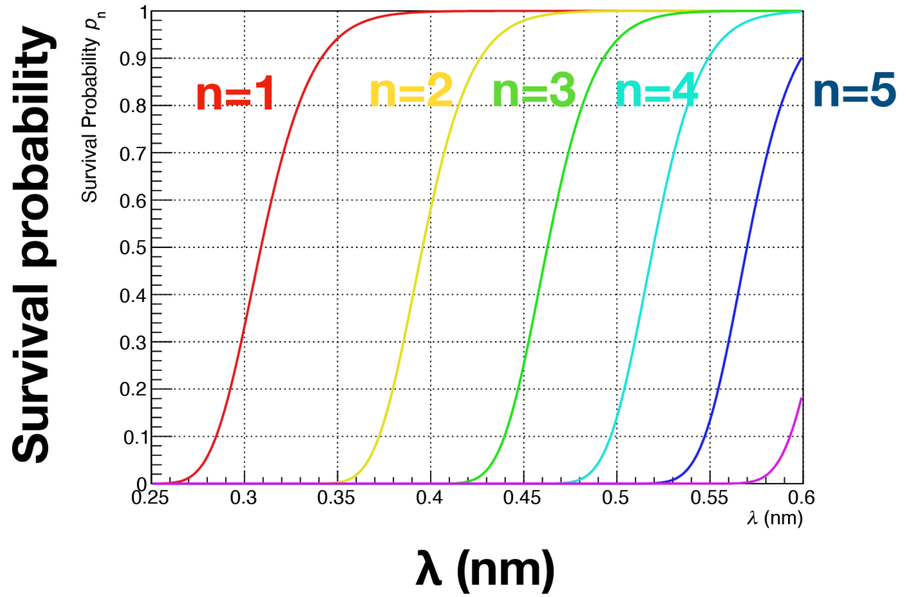
The slope deviations did not satisfy the ideal condition (slope ≪ 1.6 mrad [quantum states]). Surface waviness may therefore explain the deviations from the ideal prediction.

The surface roughness measured with a Zygo interferometer was Ra = 0.58 nm over an area of 0.08 × 0.08 mm², which is sufficiently small for this experiment.

Theoretical Calculation



Solve the Schrödinger eq. with the surface and the centrifugal potential.
Since the eigenstates are quasi-stationary, eigenenergies have imaginary parts, $\epsilon_n = \beta_n - \mathrm{i}\gamma_n$.



Wave functions are

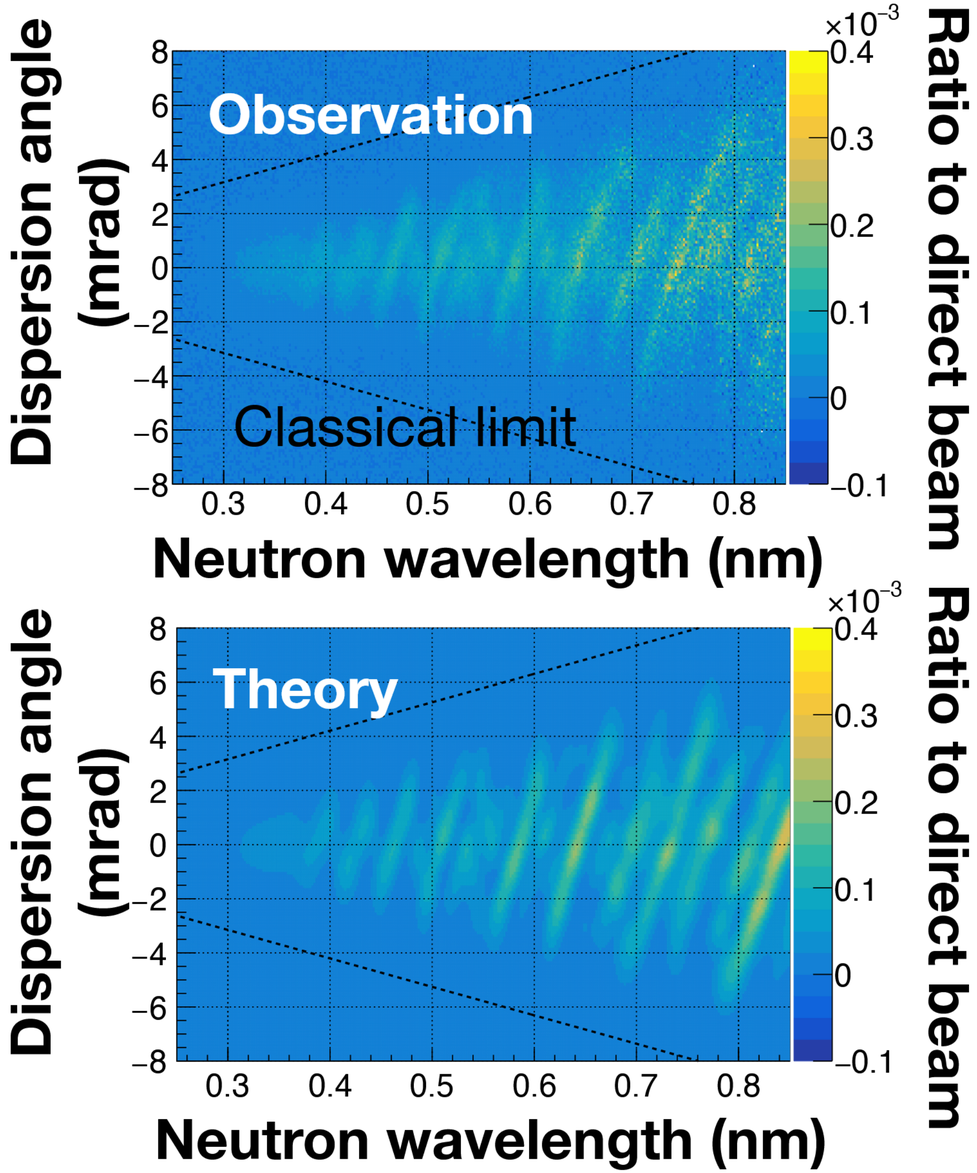
$$\chi(\zeta) = \sum_n a_n \chi_n(\zeta)\, \exp\left(-\mathrm{i}\beta_n E_0 t/\hbar\right)\, \exp\left(-\gamma_n E_0 t/\hbar\right). \qquad E_0 = \left(\frac{ma^2\hbar^2}{2}\right)^{1/3}$$

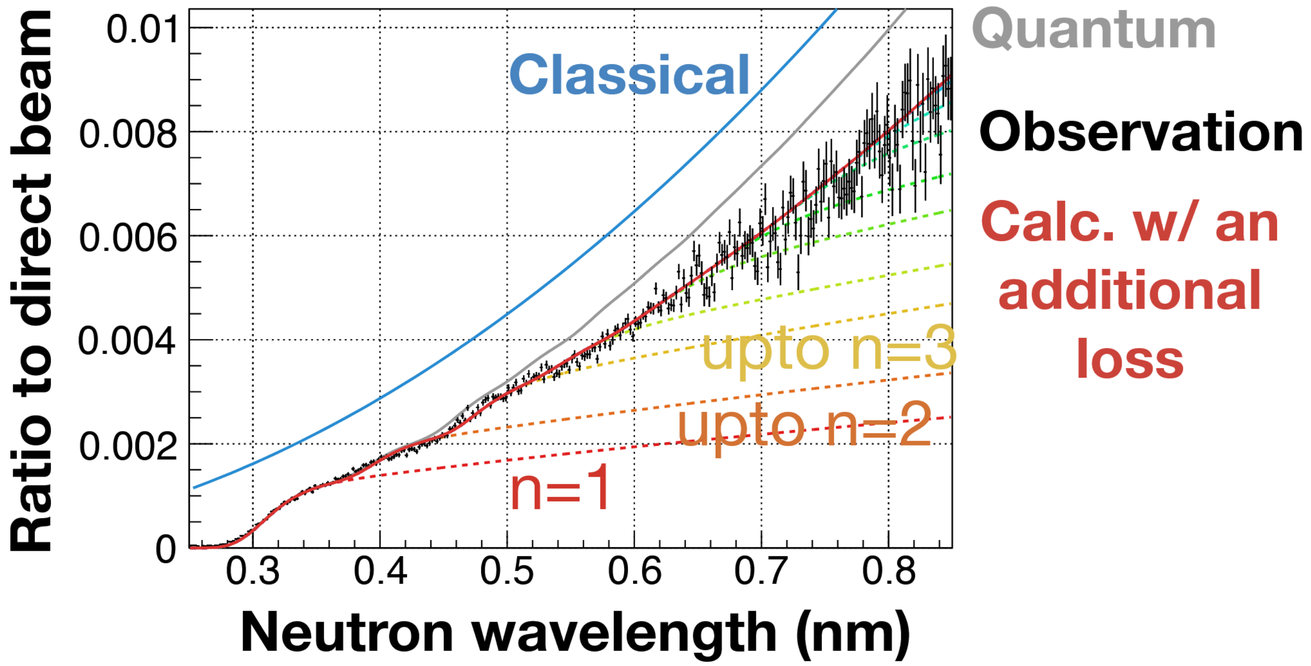
$$|\chi(\zeta)|^2 = \sum_{n,m} a_n a_m{}^* \chi_n(\zeta)\chi_m{}^*(\zeta)\, \exp\underbrace{\left[-\mathrm{i}(\beta_n - \beta_m)E_0 t/\hbar\right]}_{\text{interference}}\, \exp\underbrace{\left[-(\gamma_n + \gamma_m)E_0 t/\hbar\right]}_{\text{decay}}$$

Fourier transforming to momentum wave functions. (Deviation angle ϕ)

λ → Evolution time t

Result of neutron whispering gallery measurement



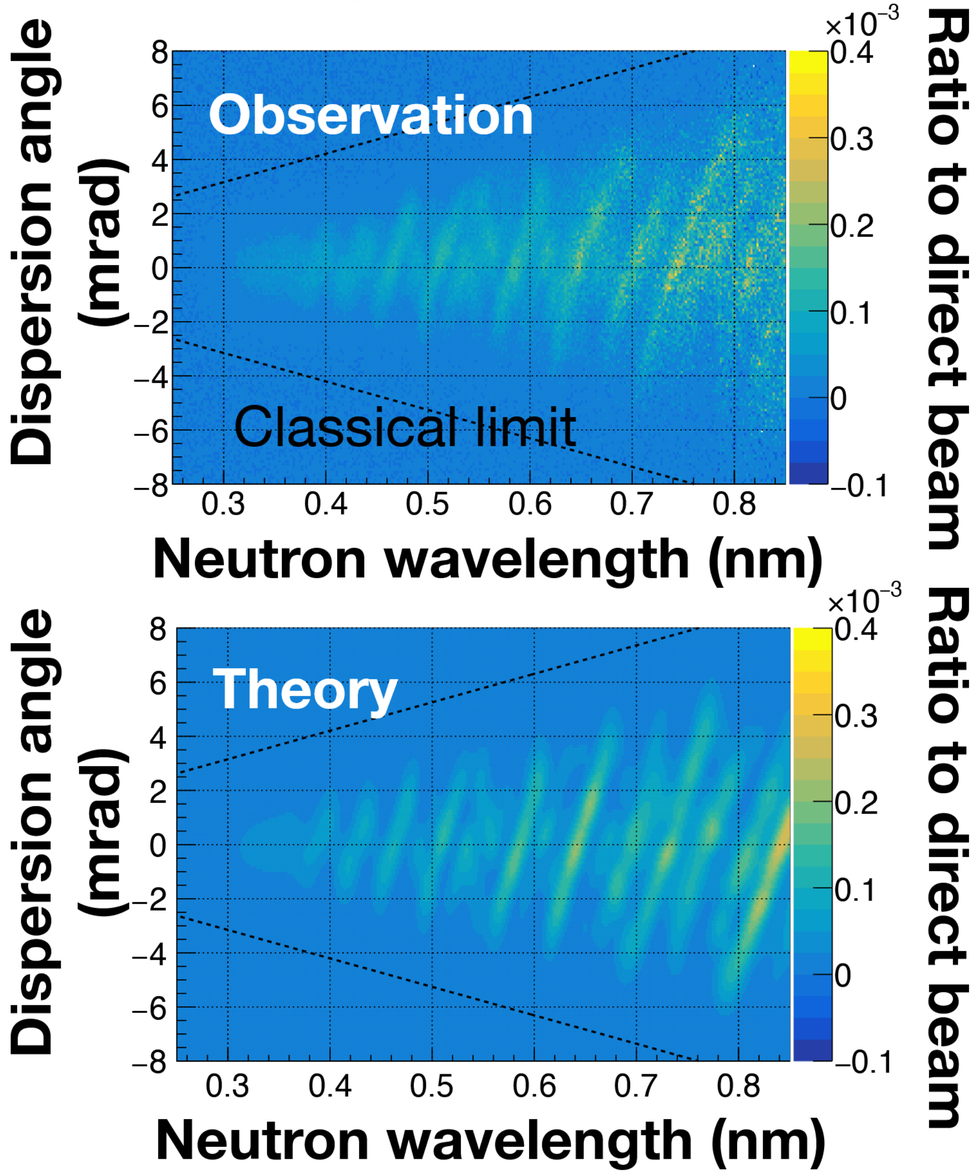


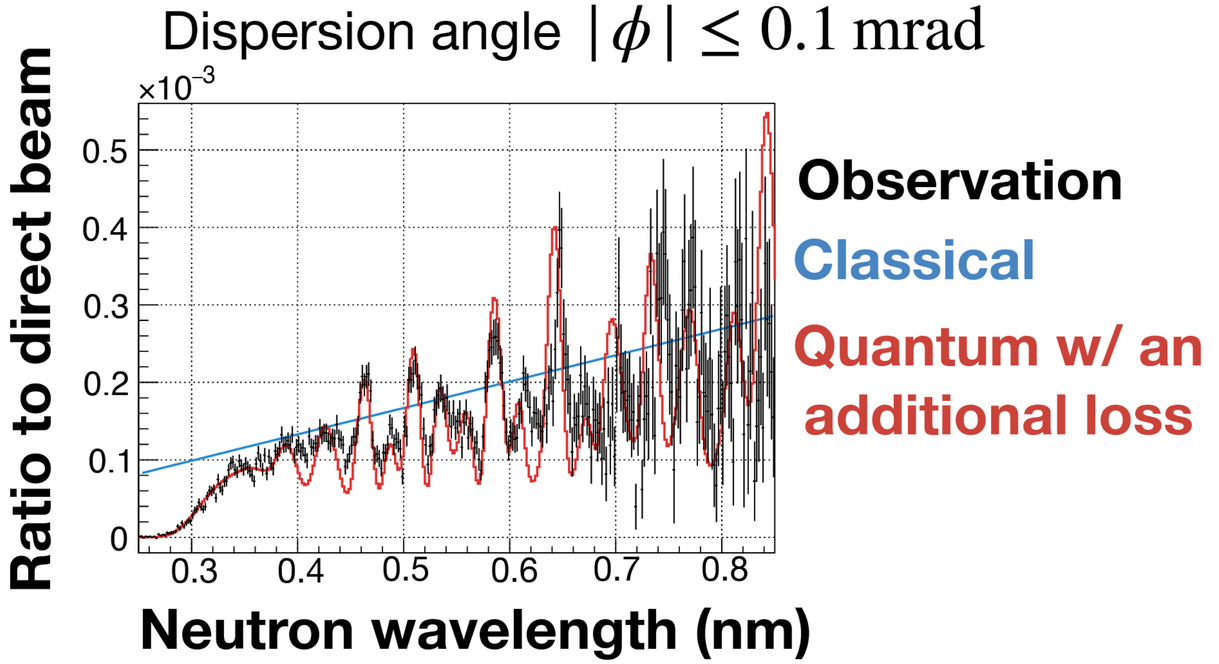
The number of counts increases in steps along the wavelength. The observed value is smaller than the quantum calculation value in the long wavelength region. With additional loss, the results become consistent.

$$\mu_n \propto \int_{U_0-E_n}^{\infty} \mathrm{d}E \frac{k}{\sqrt{2\pi}\Delta} \exp\left(-\frac{E^2}{2\Delta^2}\right)$$

$U_0 - E_n$: Potential difference
k: Loss coefficient.
Δ: Fluctuation of wall potential

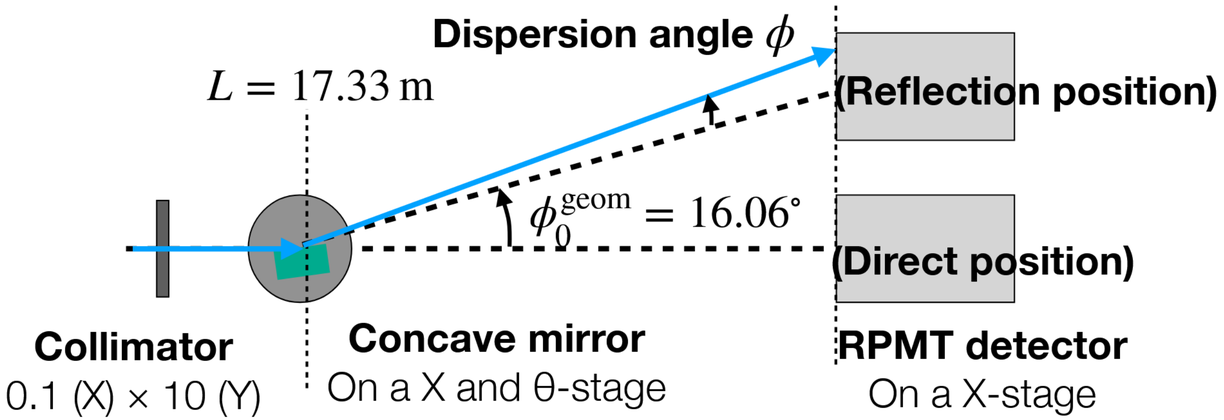
Fitting of the interference fringes





The shape of the interference fringes depends on the energy difference between the states and the evolution time on the concave mirror.
Fitting can be used to determine the angle span.
$\rightarrow \phi_0^{\mathrm{fit}} = 16.004(1)^\circ$.

Consistency and sensitivity



Method	Angle span
(A) Scattering angle	16.06(2)°
(B) Surface measurement	15.86(2)°
(C) Interference fringe fitting	16.004(1)°

The angle span of the concave mirror can be determined by the neutron's dispersion angle. →$\phi_0^{\mathrm{geom}} = 16.06(2)°$

The surface measurement of the mirror also determines the angle span. →$\phi_0^{\mathrm{surf}} = 15.86(2)°$.

This discrepancy may be caused by the mirror surface deviating from the ideal.

(C) lies between (A) and (B).
The agreement between the observation and the theory was verified to an accuracy of 1.9% in terms of centrifugal acceleration. (Difference between (A) and (B).)
The sensitivity is **10^{-4}** for the fitting result (C).

NWG as a probe for new physics

Observation of a magnetic shift in NWG states

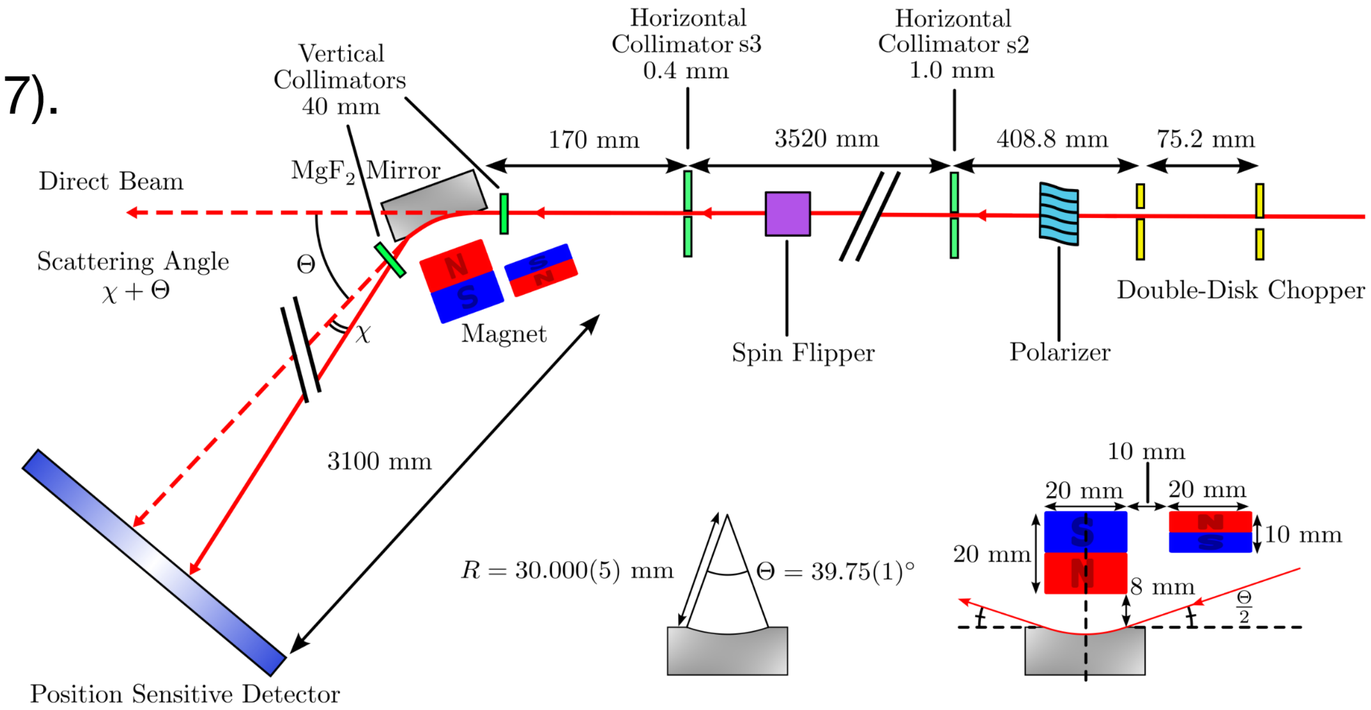
K. Schreiner, et al., arXiv:2609.25982v1 [nucl-ex]

K. Schreiner et al., including members of the group that first observed NWG states, measured a magnetic shift using polarized neutrons.

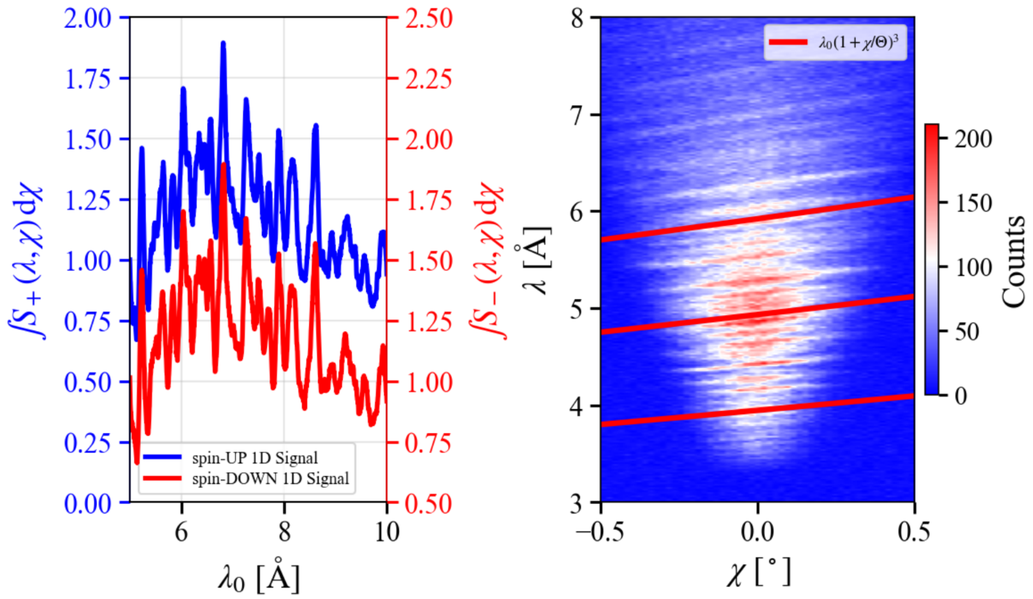
The experiment used a concave MgF_2 mirror and applied magnetic-field gradient at ILL (D17).

(~20 T/m at the concave surface)

Interference patterns were measured as functions of neutron wavelength and outgoing angle for opposite neutron spin states.



Extracting the spin-dependent shift



The 2D distributions were integrated along the interference fringes to obtain 1D profiles.

The relative shift between the two spin states was extracted from these profiles and independently from a simultaneous fit to both 2D distributions.
A spin-dependent shift was measured and consistent with the calculation. The precision is an order of 10^{-4} relative to the centrifugal acceleration. (λn=10.3 Å)

This demonstrates that NWG states can probe small spin-dependent perturbations.
→ A step to searches for new interactions

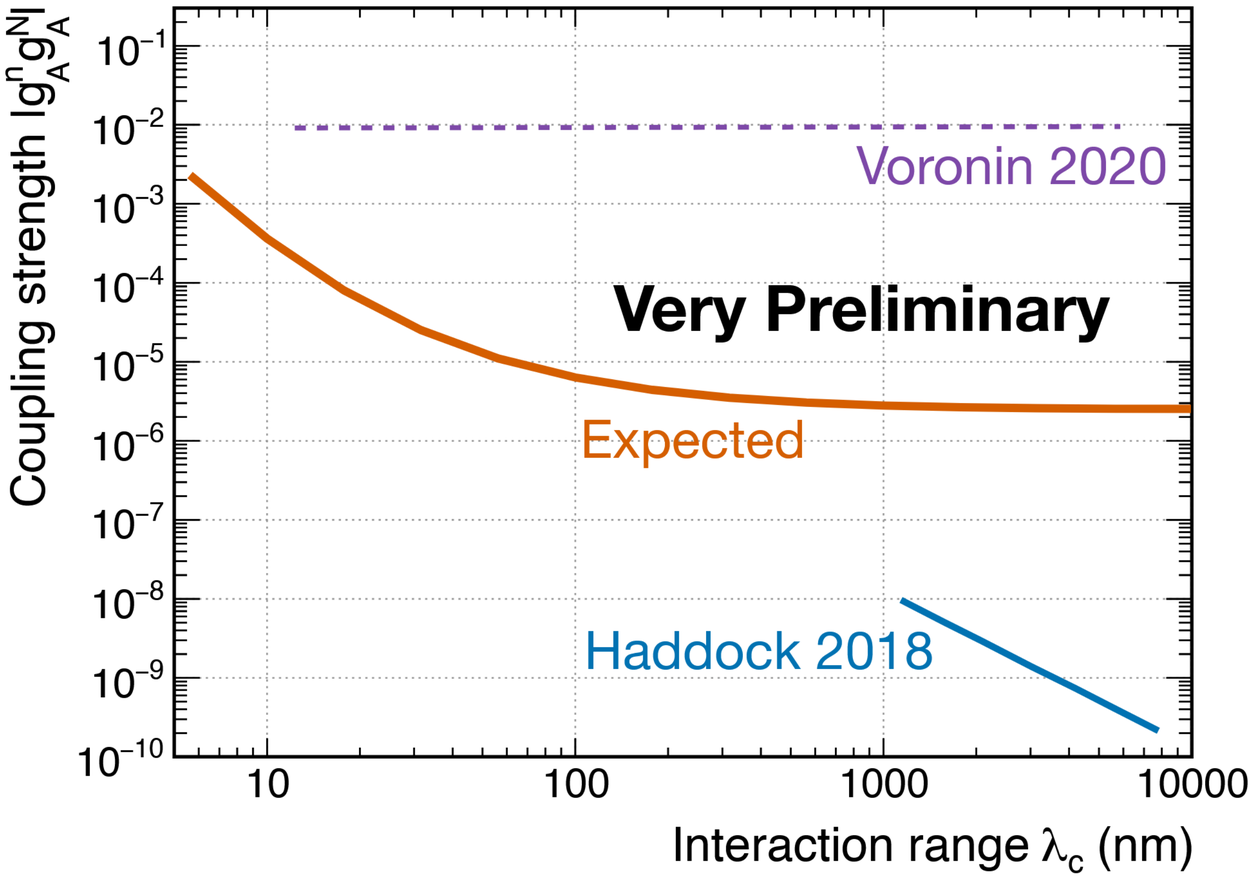
Search for spin-velocity dependent interactions

Strength

Range

$$V_{4+5} \propto \frac{g_A^{\mathrm{n}} g_A^{\mathrm{N}}}{m_n} \overrightarrow{\sigma_{\mathrm{n}}} \cdot \left(\vec{v} \times \hat{r}\right) \left(\frac{1}{\lambda_C} + \frac{1}{r}\right) \frac{\mathrm{e}^{-r/\lambda_C}}{r}$$

We can exploit the sensitivity of 10^{-4} in a search for spin-velocity dependent interactions.
The difference in the neutron interference fringes between up-spin and down-spin can be observed without displacing any items.
A very preliminary sensitivity estimation is shown on the right.

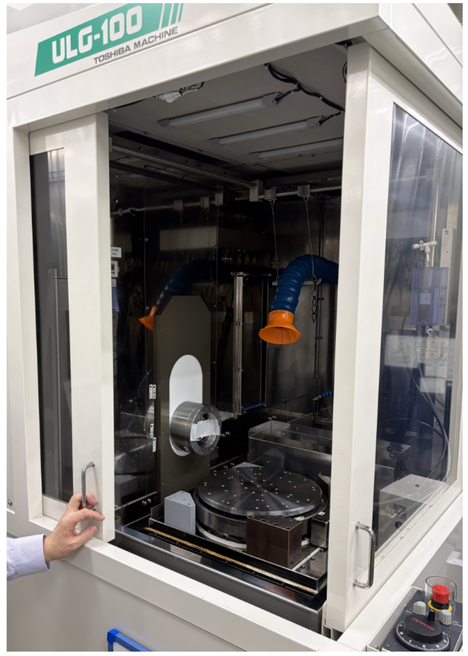


Data from other experiments are from
L. Cong, et al., Rev. Mod. Phys. 97, 025005 (2025).

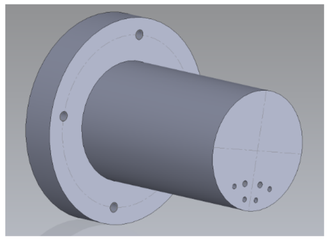
Improved concave mirror and search for new interactions

Fabrication of an improved concave mirror

We are developing a concave mirror with a more precise surface profile in collaboration with RIKEN.



Machining tool: ULG-100D

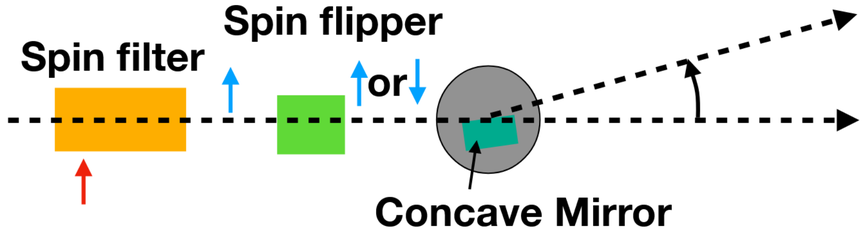


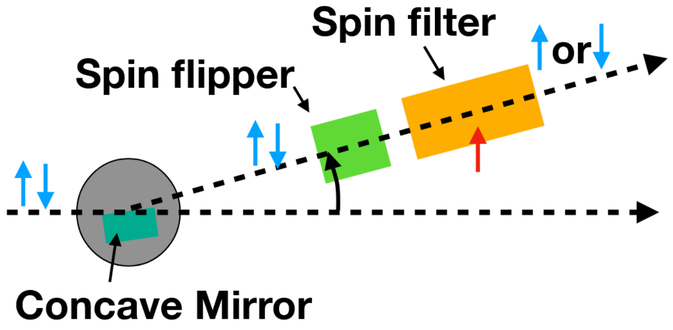
Machining jig

We will test the new concave mirror with an aluminum substrate and nickel-phosphorus plating using a neutron beam next month.

Search for neutron spin-velocity-dependent interaction

$$V_{4+5} \propto \frac{g_A^n g_A^N}{m_n} \overrightarrow{\sigma_n} \cdot \left(\vec{v} \times \hat{r}\right) \left(\frac{1}{\lambda_C} + \frac{1}{r}\right) \frac{e^{-r/\lambda_C}}{r}$$





We plan to isolate the effects of new interactions by taking the difference between spin-up and down distributions.

Summary

- GQS measurements have progressed from observing quantum states to spectroscopy and constraints on new interactions.
- At J-PARC, NWG measurements agreed with quantum calculations within 1.9%, with the accuracy limited mainly by mirror geometry.
- Interference fringe fitting achieved a relative sensitivity of ~10^{-4} to the centrifugal acceleration.
- The observed magnetic shift demonstrates that NWG states can probe a controlled spin-dependent interaction.
- Improved mirrors and polarized neutron measurements are the next steps toward searches for spin-velocity-dependent interactions.