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Neutron Pendellösung interferometry to search for exotic interactions

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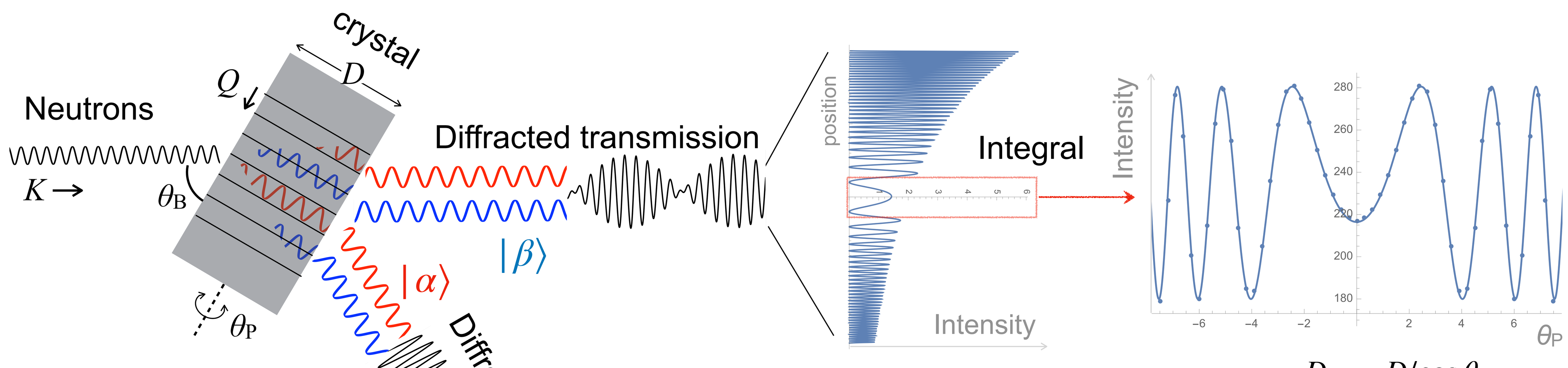
Principle and Motivations

The exotic interactions beyond standard model have been explored in experiments all over the world, however, no evidence of such interactions has yet been found. We explore the existence of exotic interactions using Pendellösung interferometry which can precisely measure the interactions acquired by neutrons.

The Pendellösung interferometry using slow neutron is observed by dynamical diffraction in a perfect crystal on Bragg condition of Laue geometry. The diffracted neutrons are described by 4 wave functions (1), in which the interference between the α state and β state is called the **Pendellösung interferogram**. The intensity fringe in the central part provides the phase shift acquired by neutrons (2). The averaged crystal potential v_Q is obtained from this phase shift, which potential includes the following physical parameters.



$$v_Q = \left(\frac{4\pi}{a^3}\sum_v e^{iQ\cdot x_v}\right)\overbrace{e^{-W}\left(b_N + \left[Z - f_e(Q)\right] b_{ne} + b_5(Q)\right)}^{b(Q)}$$

$$\mathscr{H} = \frac{\hbar^2}{2m}\begin{pmatrix} K^2 + v_0 & v_{+Q} \\ v_{-Q} & (K+Q)^2 + v_0 \end{pmatrix} \quad (1), \qquad \phi = \frac{v_Q D_{\mathrm{eff}} \lambda}{2\pi\cos\theta_B} \quad (2)$$

α state (v_{+Q}), β state (v_{-Q}), $D_{\mathrm{eff}} = D/\cos\theta_P$

Debye-Waller factor (DWF) B

It accounts for the thermal motion of the atoms in the lattice. There is potentially-interesting condensed matter physics.

$$\left\langle e^{i\vec{Q}\cdot\vec{u}}\right\rangle = e^{-W} = \exp\left[-\frac{1}{16\pi^2}BQ^2\right]$$

Nuclear scattering length b_N

This is the main contribution of $b(Q)$, which accounts for neutron and nucleon scattering. This value is measured by neutron interferometers.

$$V(\boldsymbol{r}) = \sum_j \frac{2\pi\hbar}{m} b_N \delta\left(\boldsymbol{r} - \boldsymbol{r}_j\right)$$

Mean square charge radius $\langle r_n^2\rangle$

Determinations of b_{ne} can be used to study the neutron's internal charge distribution or as a parameter in chiral effective field theory (EFT) studies of light nuclei.

$$\langle r_n^2\rangle = -6\left.\frac{dG_E^n}{dQ^2}\right|_{Q^2=0} = \frac{-3A}{2m_p^2c^2} = 86.34 b_{ne}$$

Fifth force b_5

The beyond standard model predicts the "Fifth force" as exotic interactions. Yukawa modified gravity is assumed as the general form of the fifth force, where α_G is the coupling constant and λ_5 is the interaction length.

$$V(r) = -G\frac{m_1 m_2}{r}\left(1 + \alpha_G e^{-r/\lambda_5}\right)$$

$$b_5(Q) = -\alpha_G\left(\frac{2m_n^2 MG}{\hbar^2}\right)\frac{\lambda_5^2}{1 + (Q\lambda_5)^2}$$

Experimental Results

The experiments were carried out on the NG7 Neutron Interferometry and Optics Facilities "NIOFa" in NIST NCNR. The averaged crystal potentials were measured in the (111), (220), and (400) lattice planes of the silicon perfect crystals. To remove the dominant uncertainty source which is the absolute crystal thickness, the Pendellösung experiment was combined with the Mach–Zehnder type Neutron Interferometer (NI) experiment.

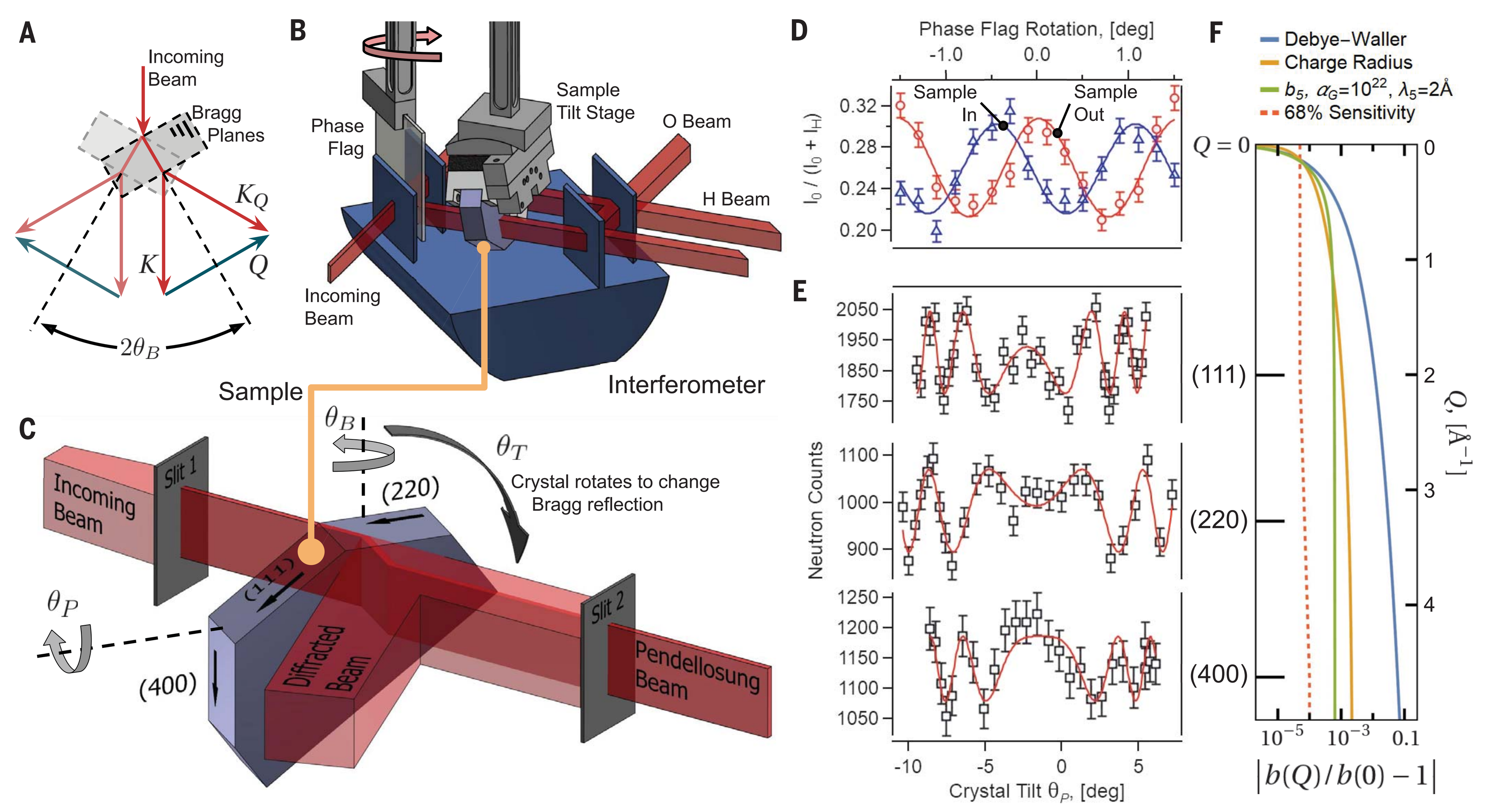
NI experiment (B) Pendellösung experiment (A,C)

$$\phi_I = C\delta + \frac{v_Q D}{H}\lambda_I N \sin\theta_{BI}, \qquad \phi_P = \frac{v_Q D \lambda_P}{2\pi\cos\theta_{BP}}$$

N; Atomic density of sample
δ; Angle of phase flag
H; Reciprocal lattice vector of NI
λ_I; Neutron wavelength in NI(B) exp.
λ_P; Neutron wavelength in Pendell.(C) exp.

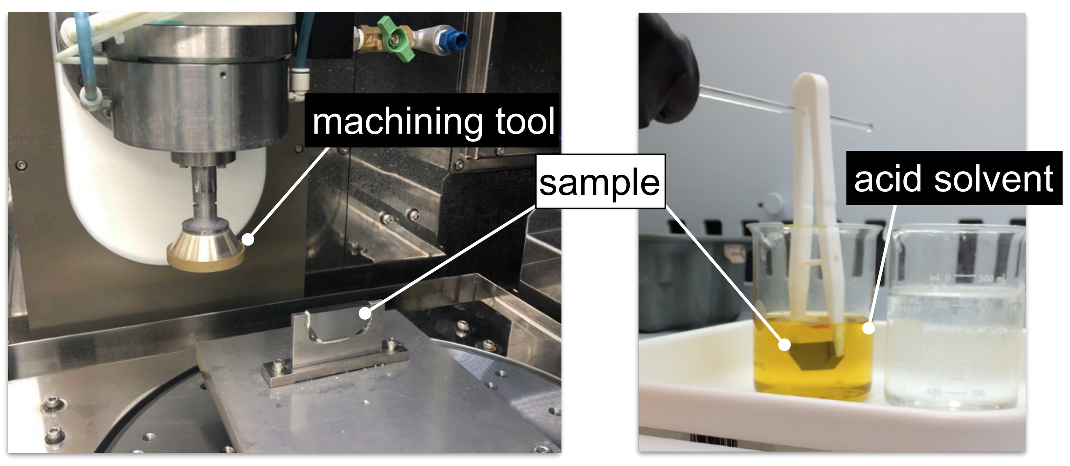
$$\frac{\phi_P}{\phi_I} = \frac{v_Q D}{v_0 D} = \frac{b(Q)D}{b(0)D} = e^{-W(Q)}\left(1 - \left(Z - f_e(Q)\right)\frac{b_{ne}}{b(0)} + \frac{b_5(Q) - b_5(0)}{b(0)}\right) \quad (3)$$

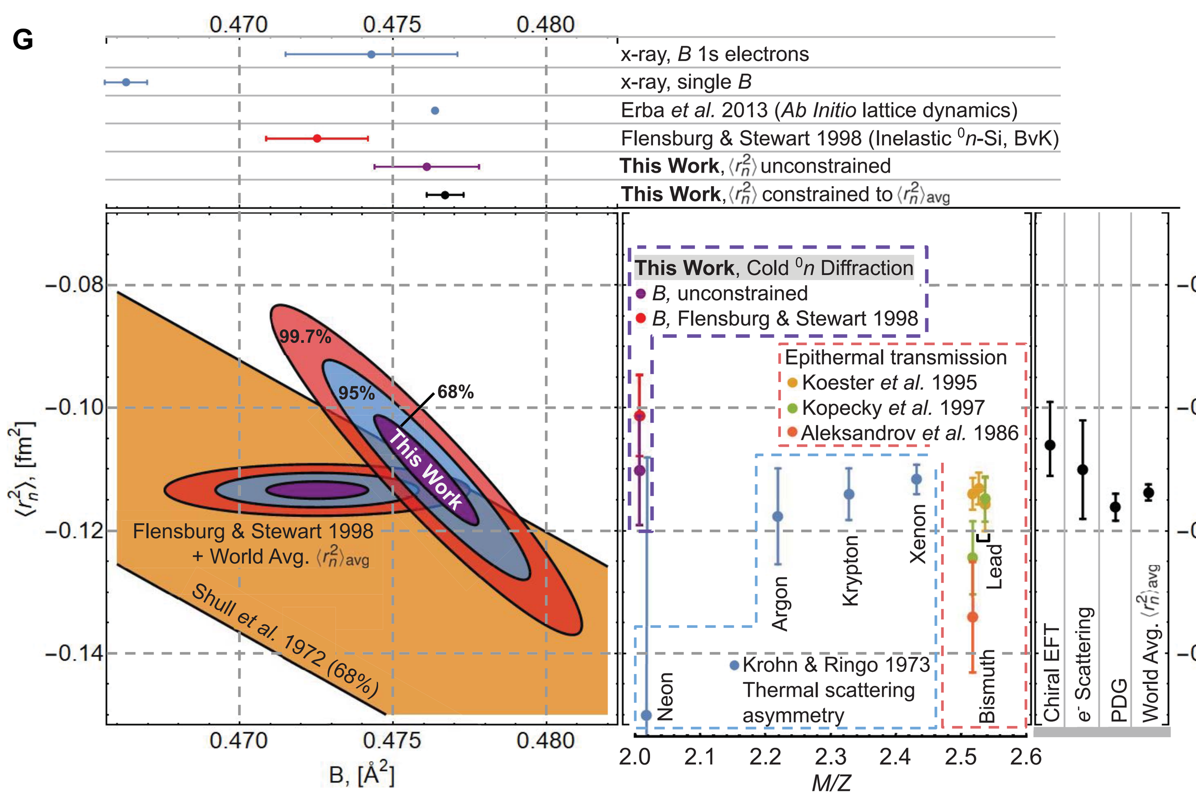
The clear interference fringes were measured from the NI experiment (D) and Pendellösung experiment (E). The total uncertainty $< 10^{-4}$ of the phase shift is less than the theoretical value of each term (F). These parameters of B, $\langle r_n^2\rangle$, and b_5 constraints were determined by Q-dependence of eq. (3). The measured $\langle r_n^2\rangle$ is consistent with the PDG value. On the other hand, the B of DWF is not consistent with the previous result of the x-ray measurement (G). It means the suggestion of breakdown in the rigid atom approximation. The constraints on the strength of the Yukawa modification to gravity were improved by an order of magnitude over the 20 pm to 10 nm length scale range (H).

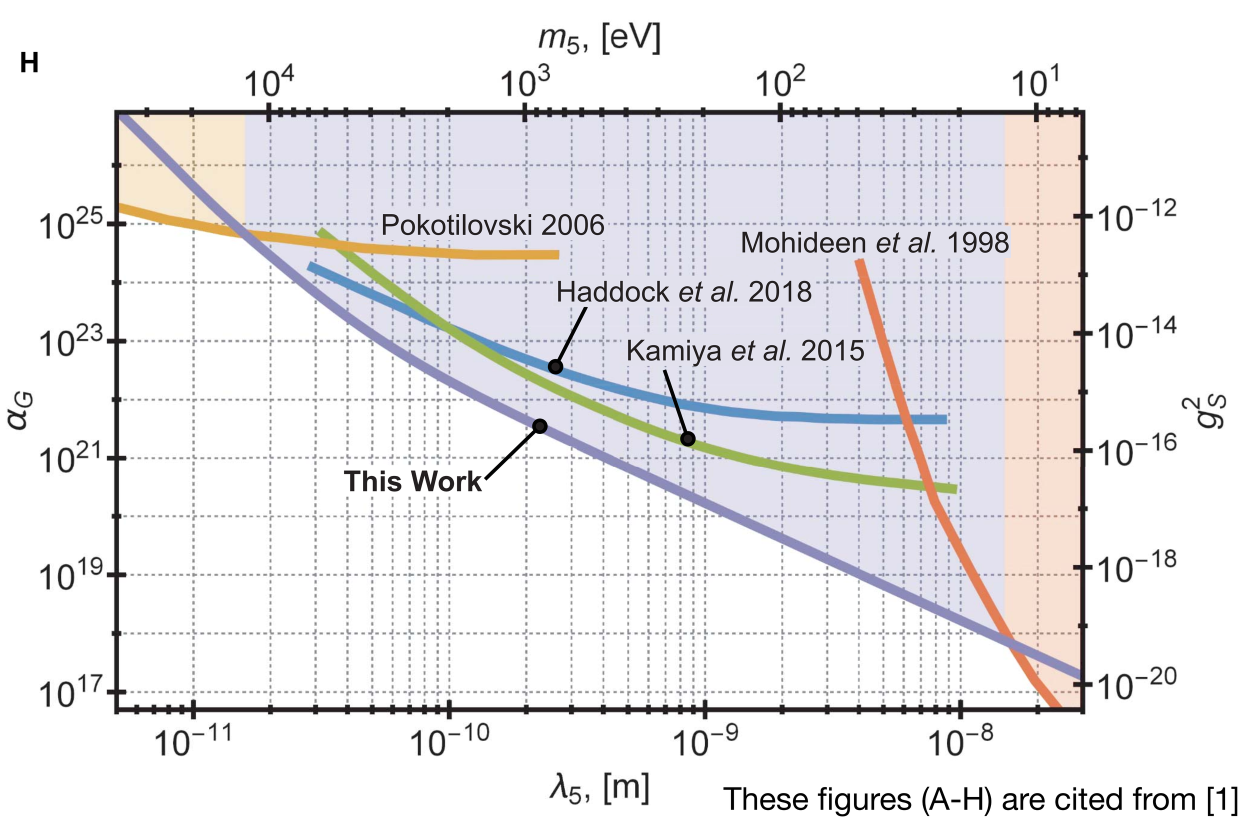


The crystal was processed to a flat & smooth surface to obtain clear fringes.

Ultra-high precision machining & Chemical etching







These figures (A-H) are cited from [1]

Conclusion and Future Plan

We explore the existence of exotic interactions predicted by the beyond standard model by precise measurement of interactions acquired by neutrons in perfect crystals. We have combined the mature technologies of the Neutron Interferometer and Pendellösung Interferometer and used advanced processing technology to achieve high-precision measurements. This experiment can probe not only the exotic interactions but also the fundamental parameters $\langle r_n^2\rangle$ and B of DWF. We plan to update the determination accuracy and constraints of these parameters with:

- Using other lattice planes → Stronger determination of Q-dependence of $b(Q)/b(0)$
- Using Germanium crystal → Constraints due to exclusion of atomic dependence
- Low-temperature measurement → Exclusion T-dependence of B of DWF

~Reference~
[1] B. Heacock et. al., Science 373 6560 (2021)
[2] B. Heacock doctoral thesis
[3] T. Fujiie master thesis