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T-Violation and Neutron Dynamical Diffraction

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Outline

1) Bragg Scattering
2) Structure Function
3) Dynamical Diffraction Hamiltonian
4) Experimental techniques and challenges

Bragg Dynamical Diffraction

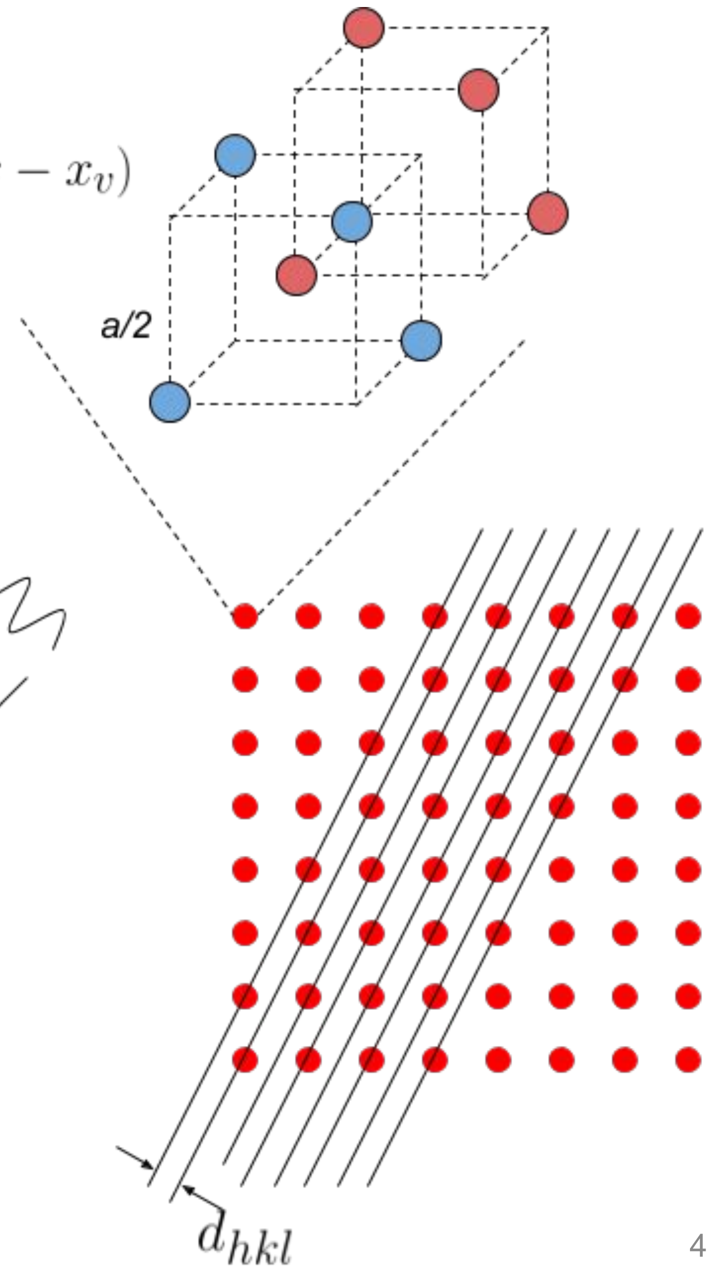
Diffraction from a periodic potential with spatial period ~ neutron wavelength

Observables that depend on the (spin and Q dependent) scattering length density of the crystal

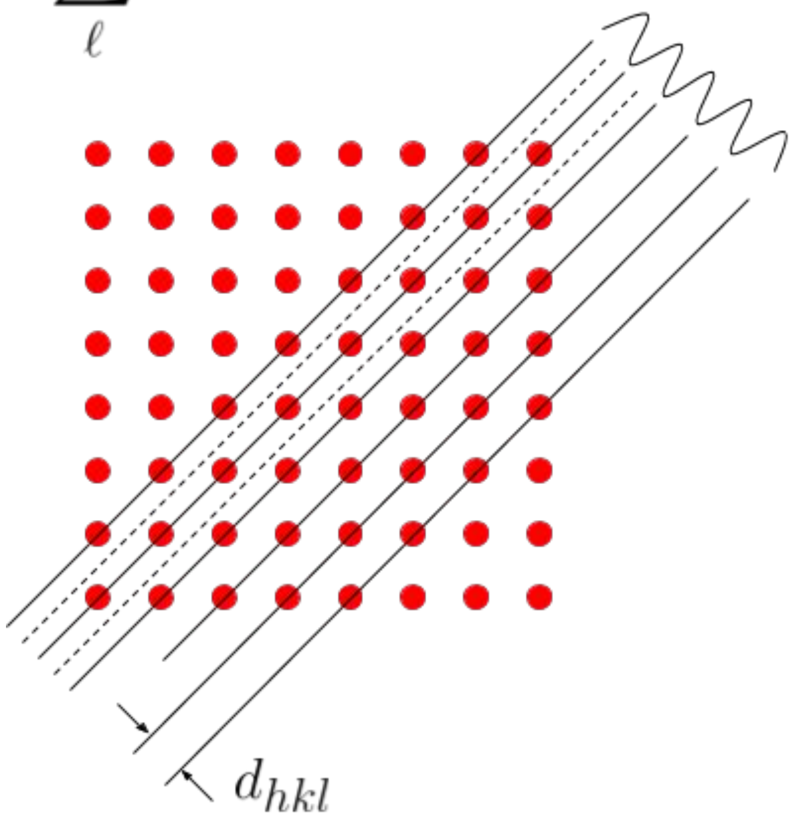
Crystal Potential

$$H = \frac{2\pi}{d_{hkl}}$$

$$V_\ell = \sum_v V_v(x - x_v)$$



$$\sum_\ell V\left(x - \ell d_{hkl}\right)$$



Bragg's Law

Diffraction occurs if the wavevector matches half the reciprocal lattice vector

Vector Law

$$-2\vec{K}\cdot\vec{H} = H^2$$

$$2KH\sin\theta_B = H^2$$

Reflectivity of radiation that deviations from Bragg, depends on the strength of the interaction between the radiation and the scattering centers

Bragg Scattering

Geometrically select very specific *Q* according to a discrete Fourier transform

$$\sum_{\ell} e^{i\vec{Q}\cdot\vec{x}_\ell} = \frac{(2\pi)^3}{\Omega_0}\delta^{(3)}\left(\vec{Q}-\vec{H}\right)$$

Intensity and width of momentum space acceptance given by the scattering length density of the crystal

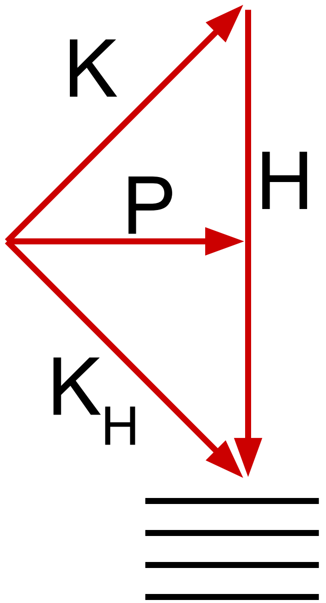
$$2\vec{K}\cdot\vec{H} = -H^2$$

$$\delta\vec{K}\cdot\vec{H} = v_H$$

Neutron Structure Factor

$$v_H = \frac{2m}{\Omega_0} \sum_v \widetilde{V}_v\left(\vec{H}\right)\left\langle e^{i\vec{H}\cdot\vec{x}_v}\right\rangle$$

A stronger spatially (temporally) oscillating potential lessens the beating period between states



$$\Delta_H = 2\pi \frac{P}{v_H}$$

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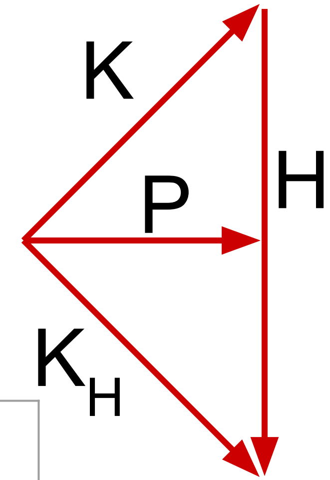
Potentials and Symmetry

Potential dominated by nuclear scattering

$$\widetilde{V}_N = \frac{2\pi}{m} b_N$$

$$b_N \to b\left(\vec{Q}\right)$$

$$b\left(\vec{Q}\right) = b^*\left(-\vec{Q}\right)$$



Spin-Dependence

Spin-Dependence	Coupling	Notes
None	$g_V^2,\ g_S^2$	Multiple H
$\frac{i}{2m}\vec{H}\cdot\vec{\sigma}$	$g_s g_p,\ d_n$	Non-Centrosymmetric
$\frac{i}{2m^2}\left(\vec{H}\times\vec{P}\right)\cdot\vec{\sigma}$	$g_V^2+g_A^2$	Schwinger, Non-centrosymmetric
$\frac{1}{2m}\vec{P}\cdot\vec{\sigma}$	$g_V g_A$	Parity violating

$$\mathcal{L}_{\rm int} = Z'_\mu \bar{\psi}\gamma^\mu(g_V + g_A\gamma^5)\psi$$

$$\mathcal{L}_{\rm int} = -\phi\bar{\psi}(g_S + i\gamma^5 g_P)\psi$$

$$\mathcal{L}_{\rm int} = -\frac{i}{2}g_d a\bar{\psi}\sigma_{\mu\nu}\gamma^5\psi F^{\mu\nu}$$

Effective E-Field ~ 10^8 V / cm

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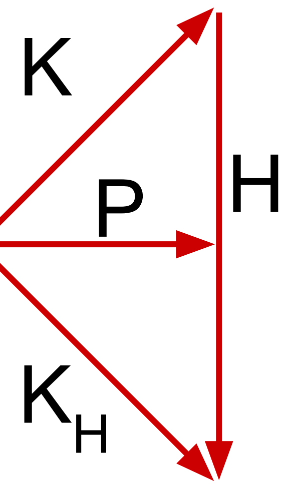
Forms of b_5



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

$$b_5(H,\sigma) \propto \begin{cases} -\frac{g^2}{2m}\left(\frac{\lambda_5^2}{1+(H\lambda_5)^2}\right)\ \vec{P}\cdot\vec{\sigma} \\ -\frac{ig^2}{2m^2}\left(\frac{\lambda_5^2}{1+(H\lambda_5)^2}\right)\left(\vec{P}\times\vec{H}\right)\cdot\vec{\sigma} \\ -\frac{ig^2}{2m}\left(\frac{\lambda_5^2}{1+(H\lambda_5)^2}\right)\vec{H}\cdot\vec{\sigma} \end{cases}$$

T-Violating and Schwinger Terms

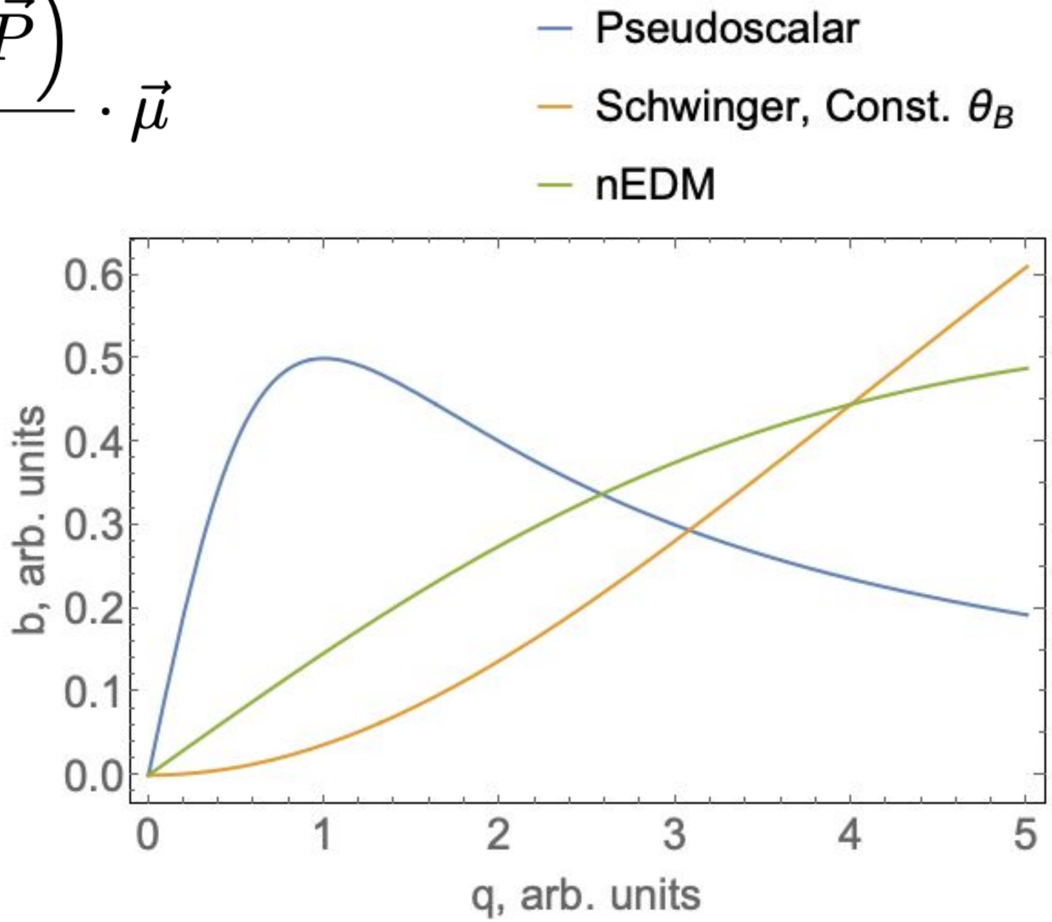
$$b_{dn} = i\frac{2m}{H^2}\,\widetilde{\rho}\left(H^2\right)\vec{H}\cdot\vec{d}_n \qquad b_{SP} = -i\frac{g_s g_p}{4\pi}\frac{\lambda_5^2}{1+\left(H\lambda_5\right)^2}\vec{H}\cdot\vec{\sigma}$$

$$b_{\mathrm{Sch}} = i2\,\widetilde{\rho}\left(H^2\right)\frac{\left(\vec{H}\times\vec{P}\right)}{H^2}\cdot\vec{\mu}$$

$$\widetilde{\rho}\left(H^2\right) \sim Ze\left[1-f(H)\right]$$

$$f(q) \sim \frac{1}{\sqrt{1+3\left(\frac{q}{q_0}\right)^2}}$$

$$q_0 \sim 1.9Z^{1/3}\ \mathrm{\AA}^{-1}$$



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Dynamical Diffraction Hamiltonian

$$H = \frac{\hbar^2}{2m}\begin{pmatrix} K^2 + v_0 & v_{-H} \\ v_H & K_H^2 + v_0 \end{pmatrix}$$

$$K^2 - k^2 = -v_0 - \delta\vec{K}\cdot\vec{H} \pm \sqrt{\left(\delta\vec{K}\cdot\vec{H}\right)^2 + v_H v_{-H}}$$

Index of refraction depends on deviation from Bragg, and +/- state

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Potentials and Symmetry

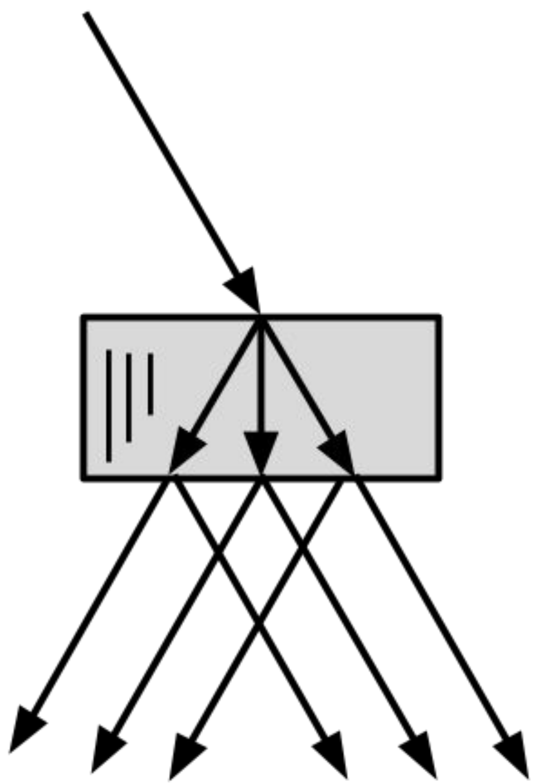
Spin-Rotation in crystal depends on

$$v_H v_{-H} = \left(\frac{4\pi}{\Omega_0}\right)^2 \left| \sum_v \left(b_N + i|b_\mathrm{T}|\right) e^{i\vec{H}\cdot\vec{x}_v} \right|^2$$

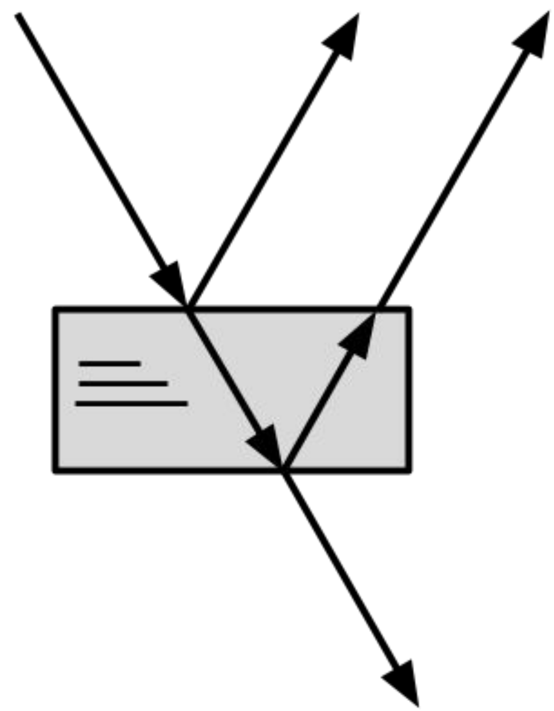
Interference between scattering sites required for terms first order in b_T

Excitation of Internal States from External Source Wave

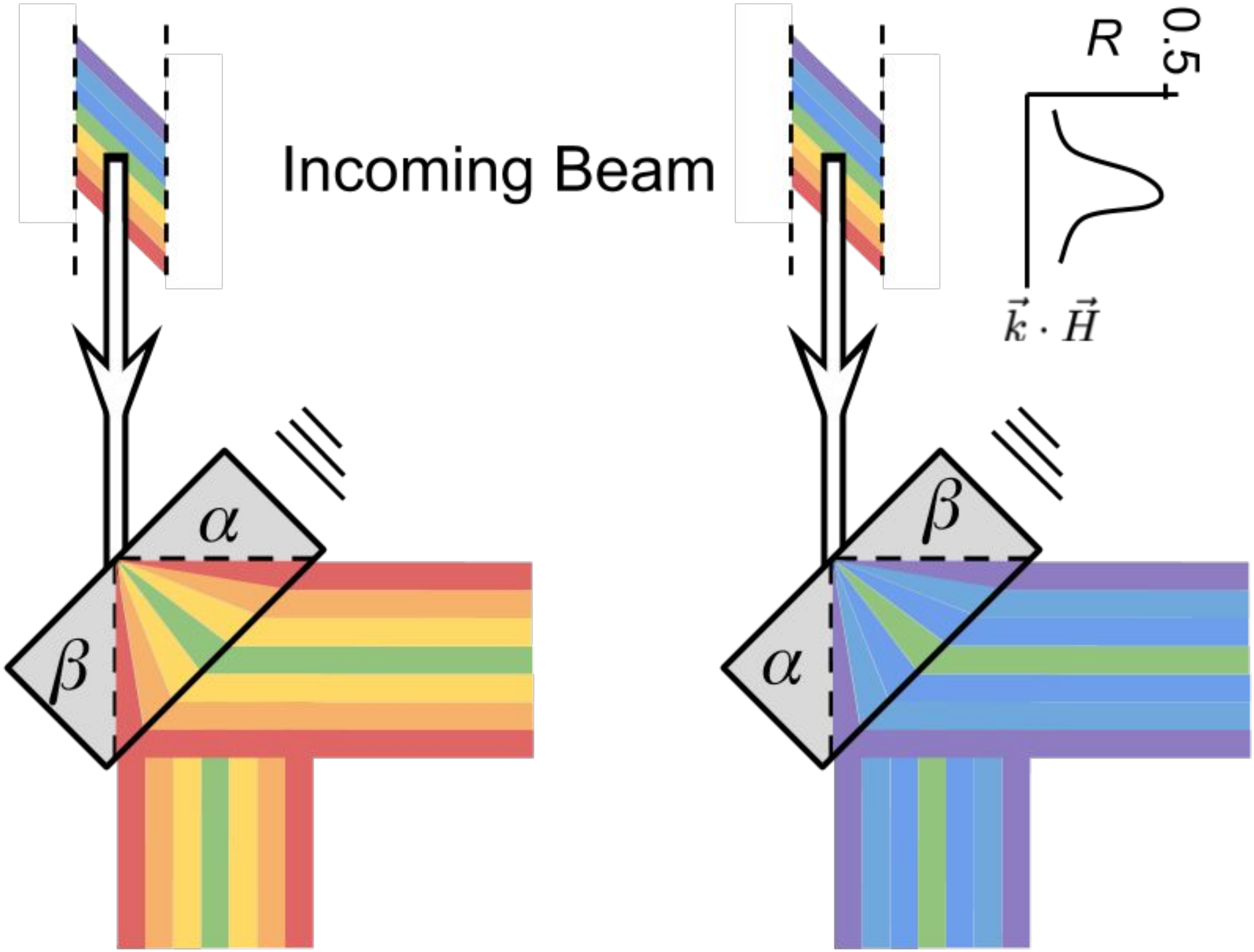
Laue Case: Bragg misalignment conserved across the boundary



Bragg Case: wave vector parallel to the Bragg planes is conserved



Modified Dispersion



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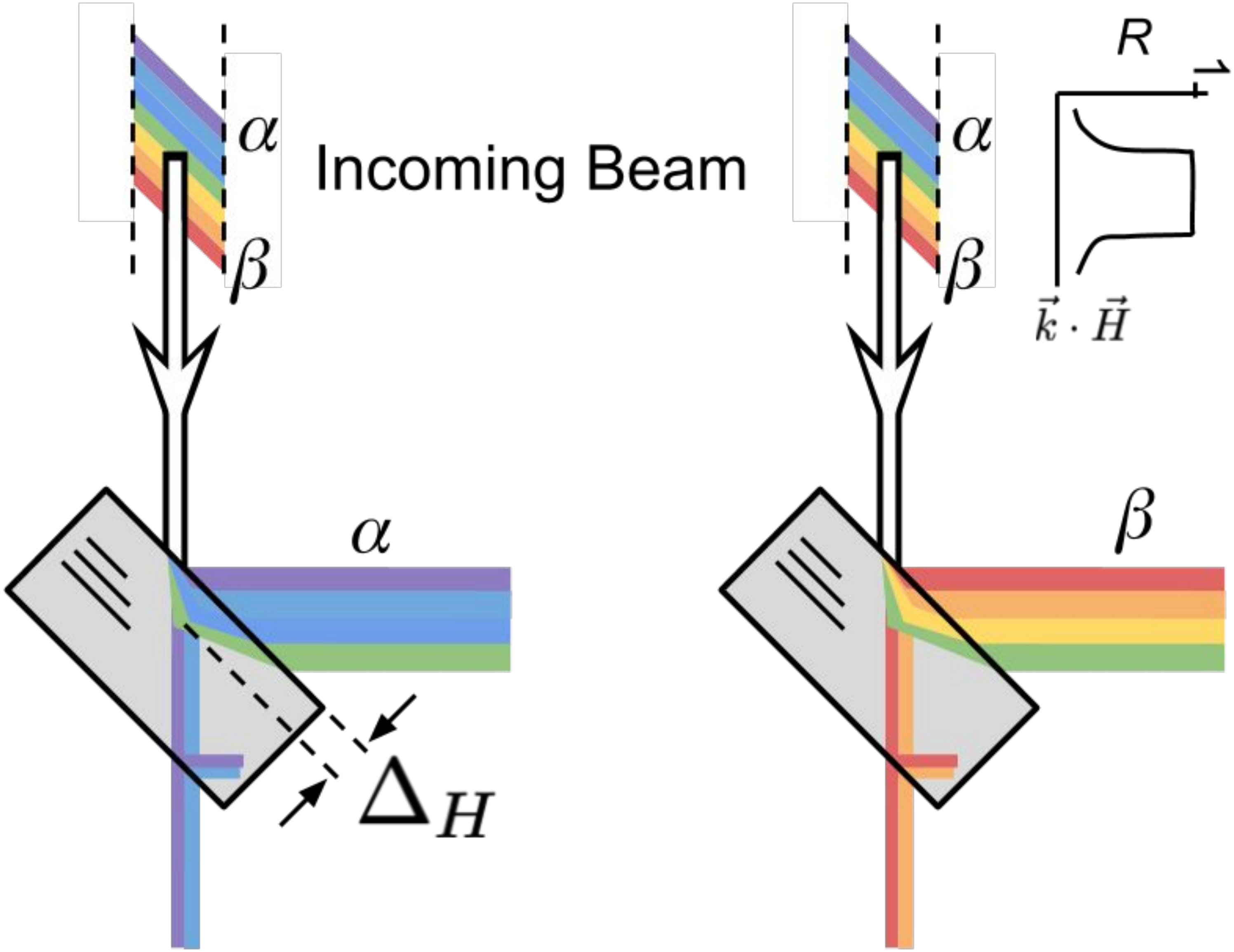
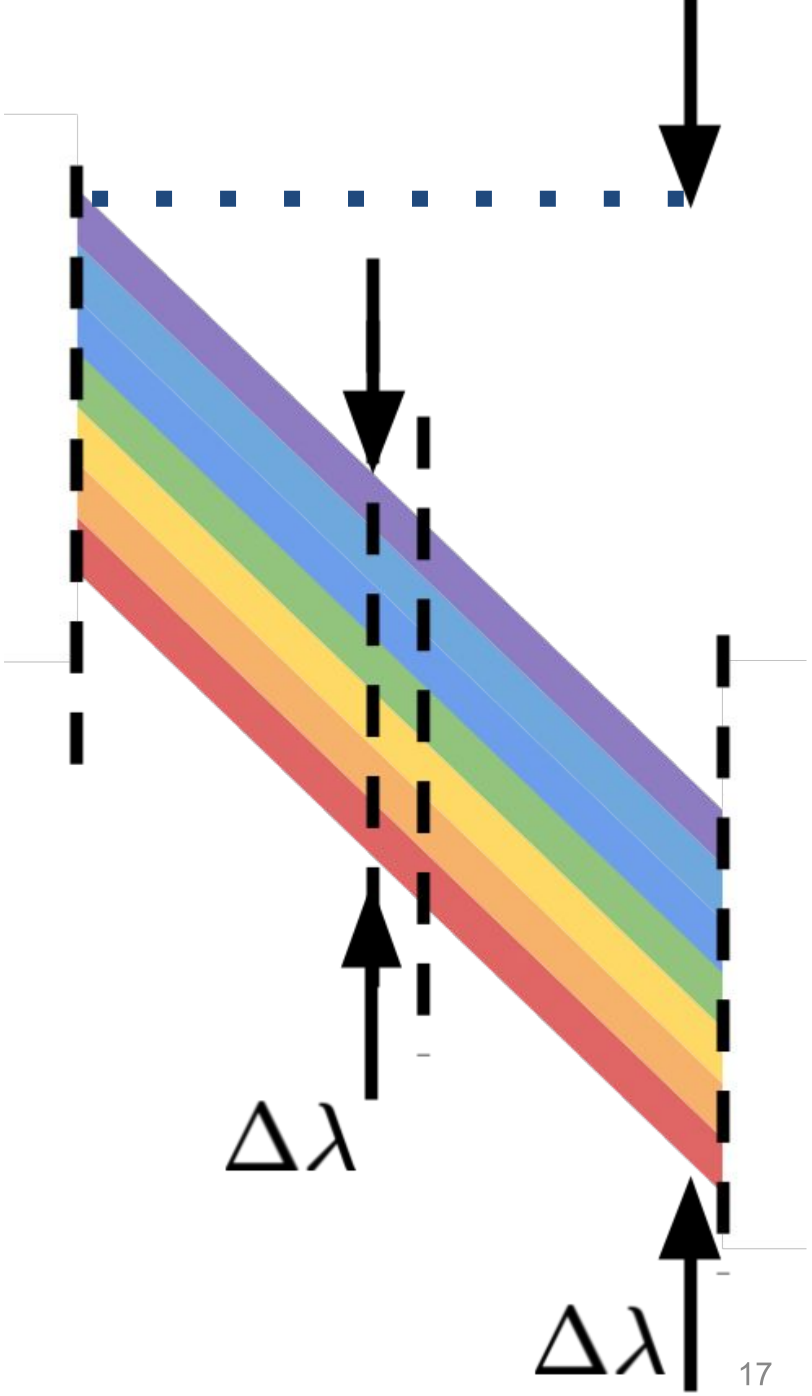


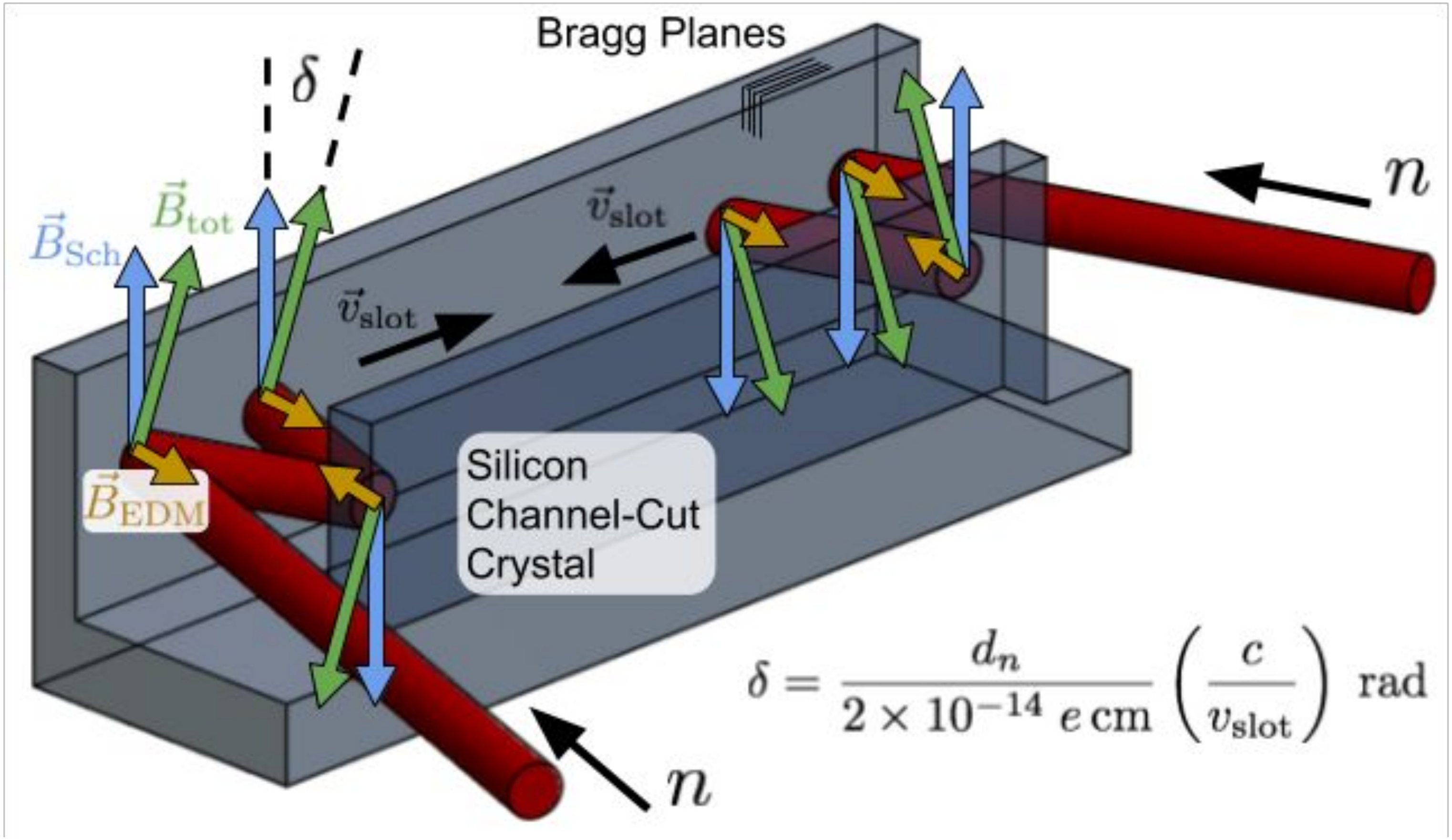
Collimation

Collimation effects wavelength spread



Effective B Fields

All fields reversed for $\alpha \rightarrow \beta$ crystal states!



Theory Summary

Incoming wave excites two states within the crystal

Those two states correspond to an increase or decrease in the refractive index which depends on Bragg misalignment

Structure function gives spin and momentum dependence to diffraction operators

Observables

Intensity

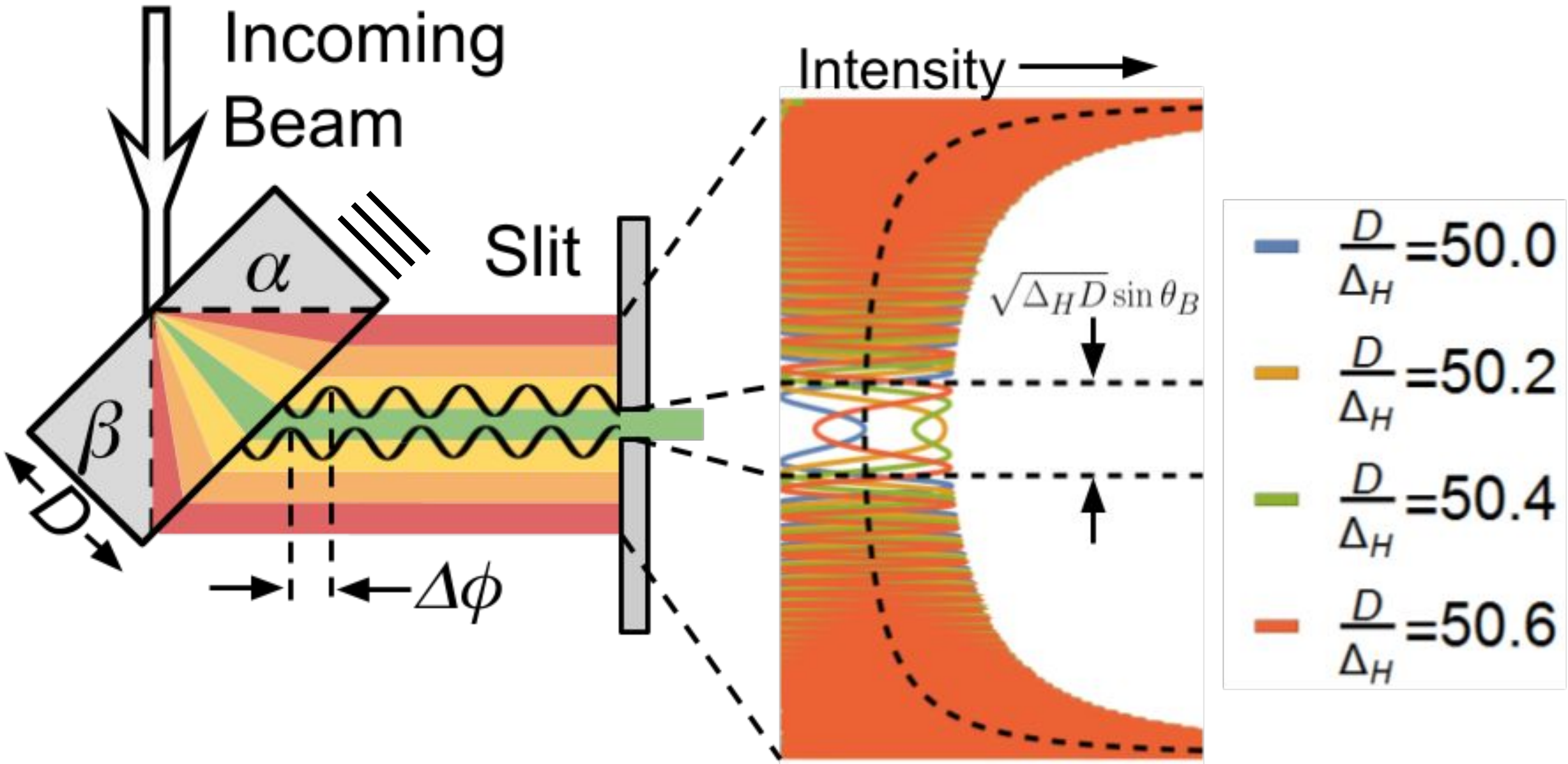
FWHM of Bragg peak

Pendellosung

Spin Rotation

Traps

Pendellösung



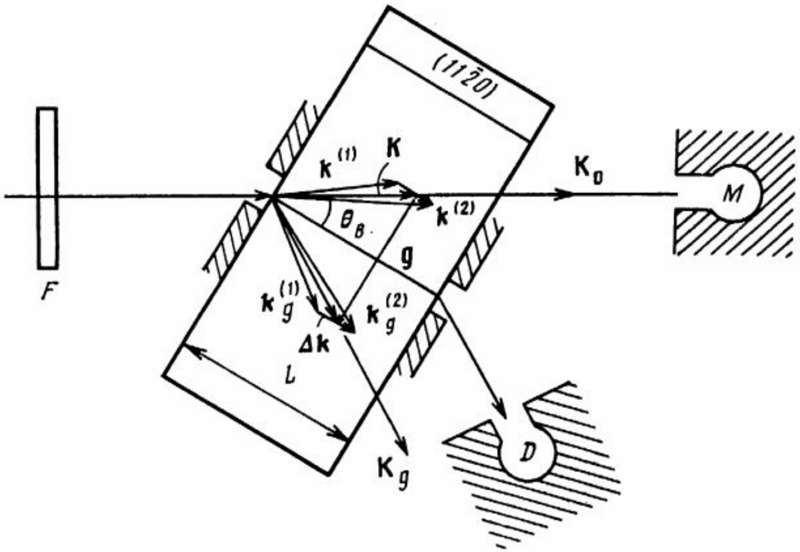
$$\Delta\phi = 2\pi\frac{D}{\Delta_H} \sim 2\pi\frac{10\ \text{mm}}{40\ \mu\text{m}} \simeq 2\pi(250)$$

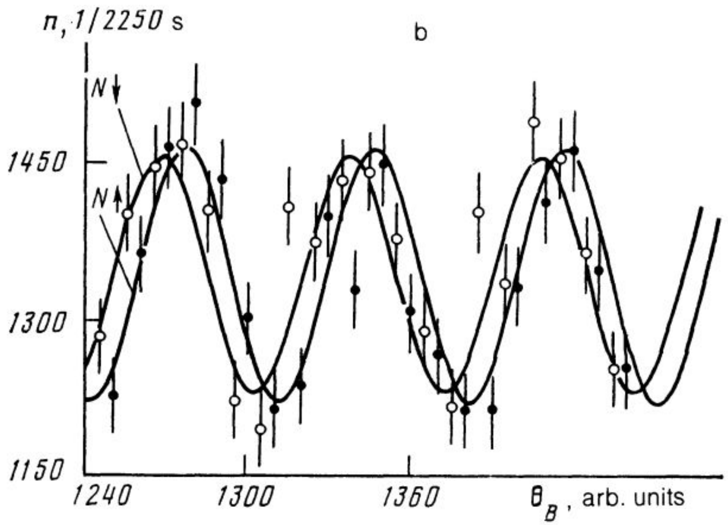
$$\Delta\phi \propto D\lambda$$

Vary *D* or λ to measure $\Delta\phi$ modulo 2π

Pendellosung to measure $\widetilde{\rho}(\vec{q})$

Use Schwinger scattering and phase shift between two spin states





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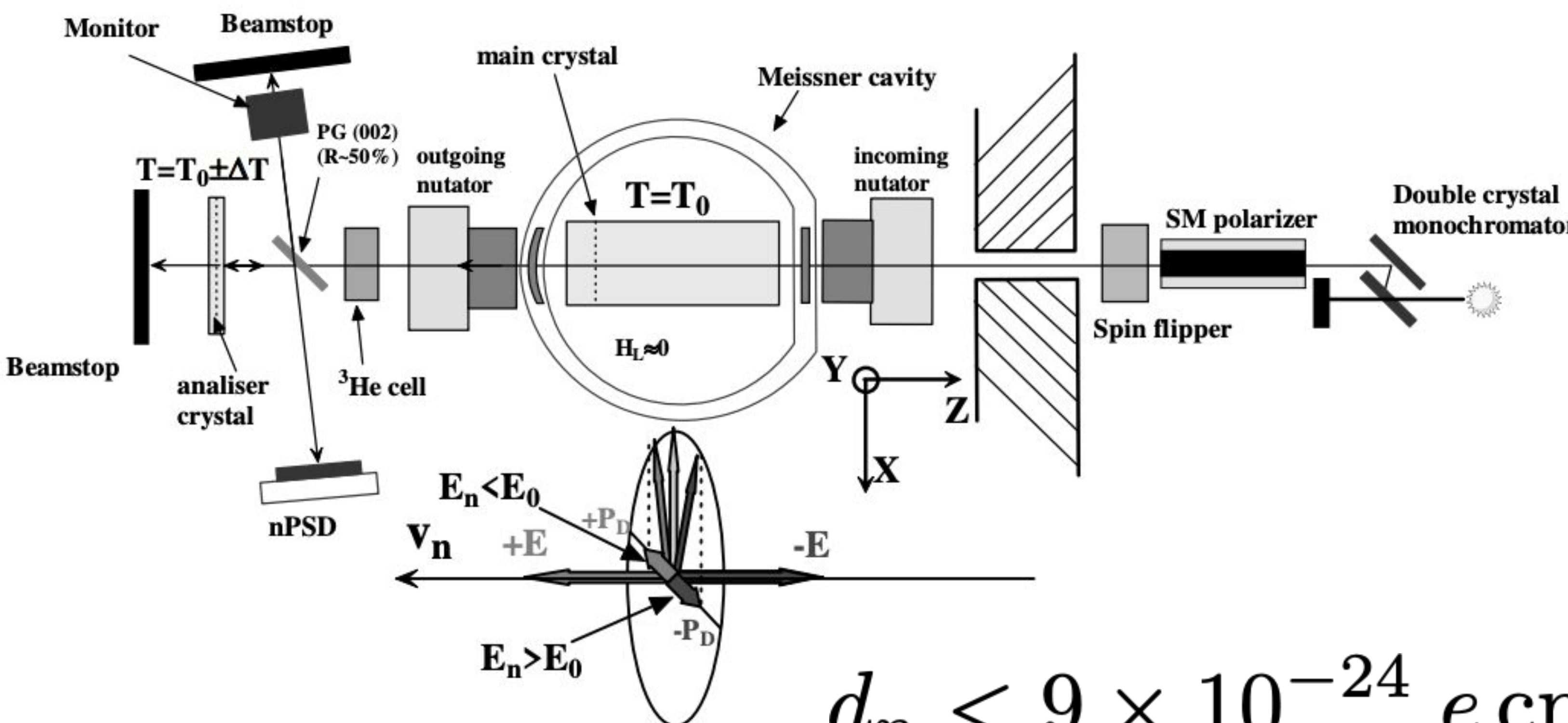
Spin Transport



$$d_n < 9 \times 10^{-24}\, e\,\mathrm{cm}$$

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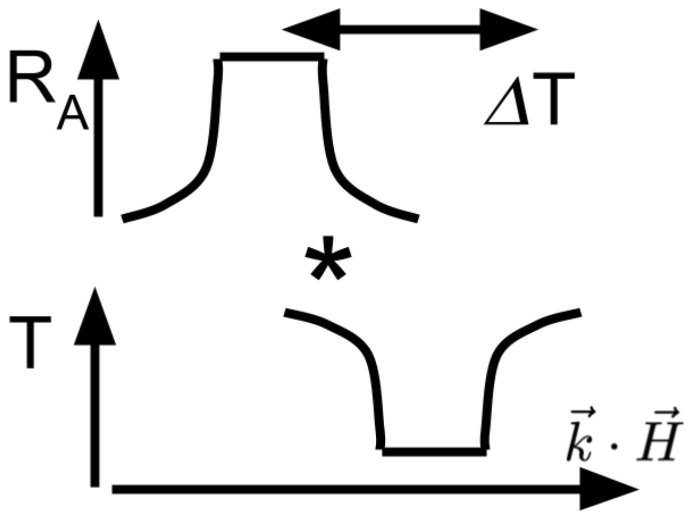
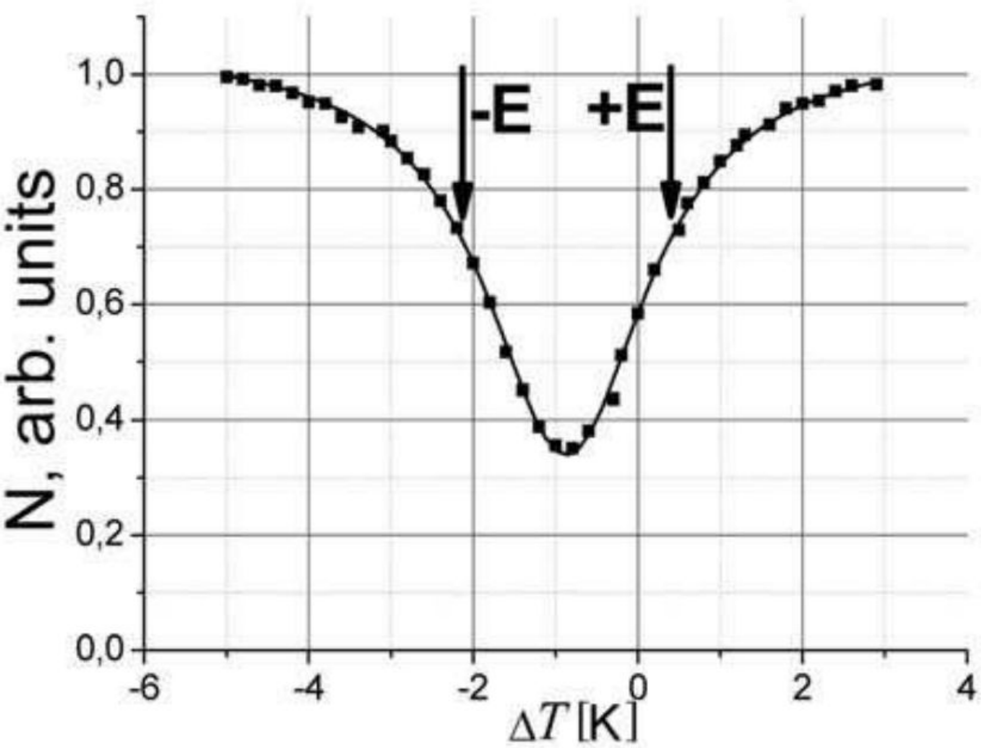
Spin Transport





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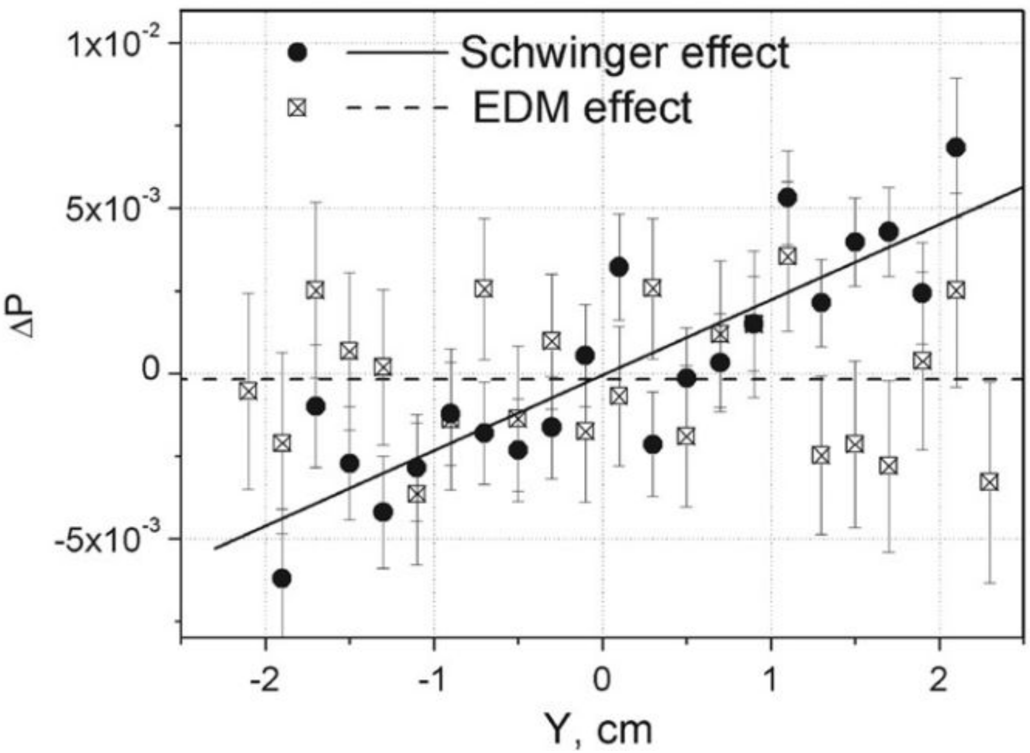
Spin Transport



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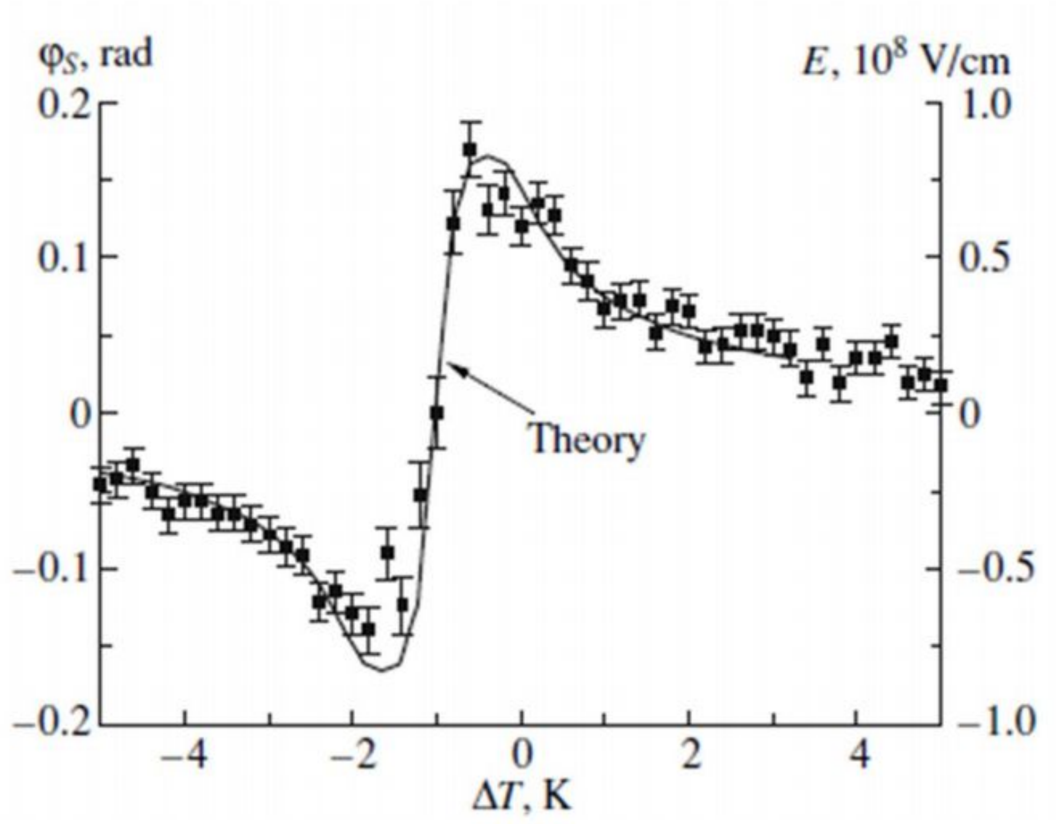
Spin Transport



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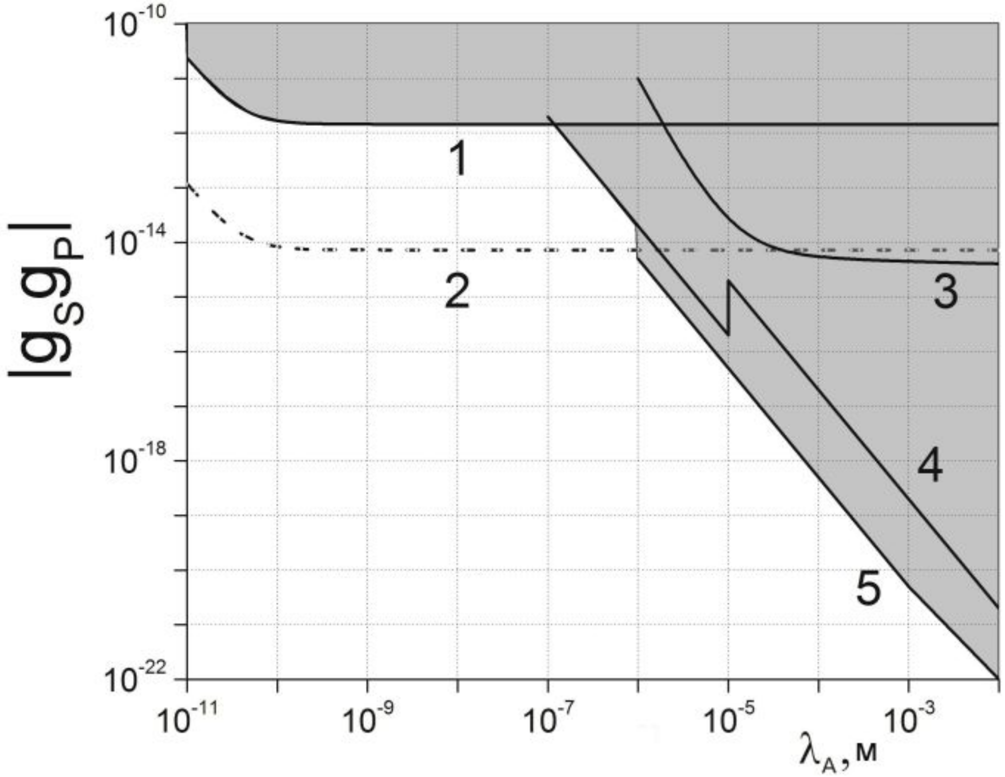
Sensitivity to Pseudoscalar



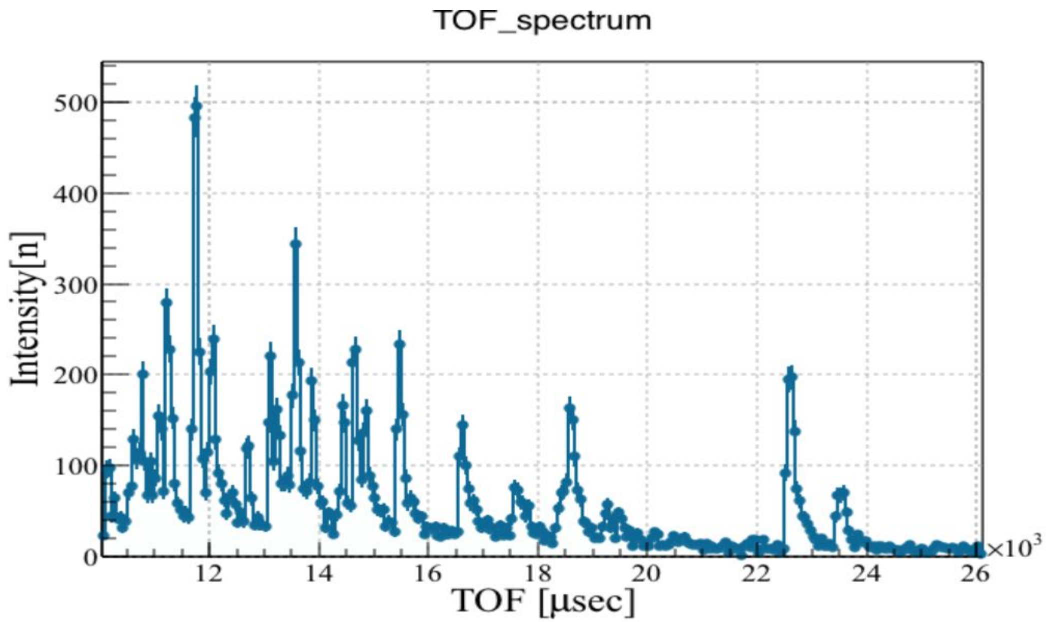
1) Crystal nEDM
2) Improved xtal nEDM
3) Bouncing neutrons
4) UCN Storage
5) ^{3}He Storage

Fedorov, V.V. and Voronin, V.V., 2018. Modern Status of Searches for nEDM, Using Neutron Optics and Diffraction in Noncentrosymmetric Crystals. In *Proceedings of the International Conference on Neutron Optics (NOP2017)* (p. 011007).

Pulsed Source Advantages

Multiple Bragg Conditions Simultaneously

Trapping Fraction



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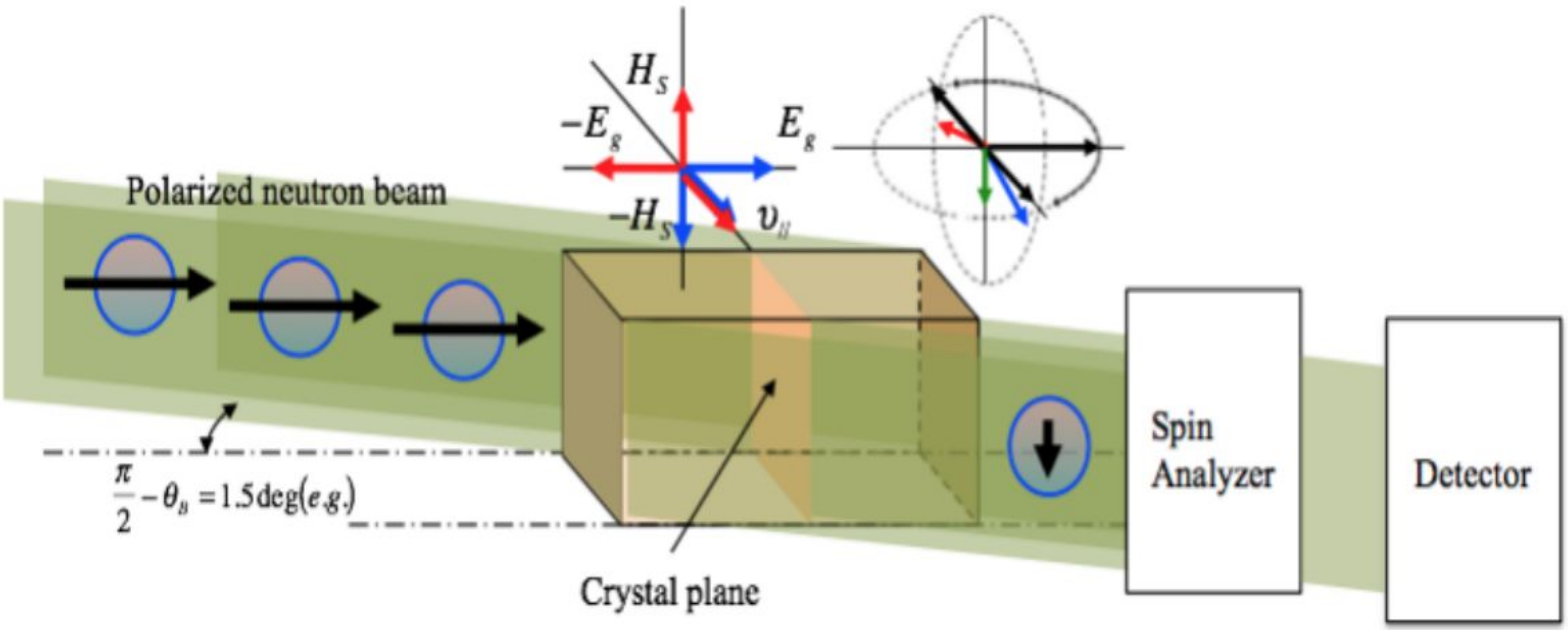
Laue Spin Transport with a Pulsed Source



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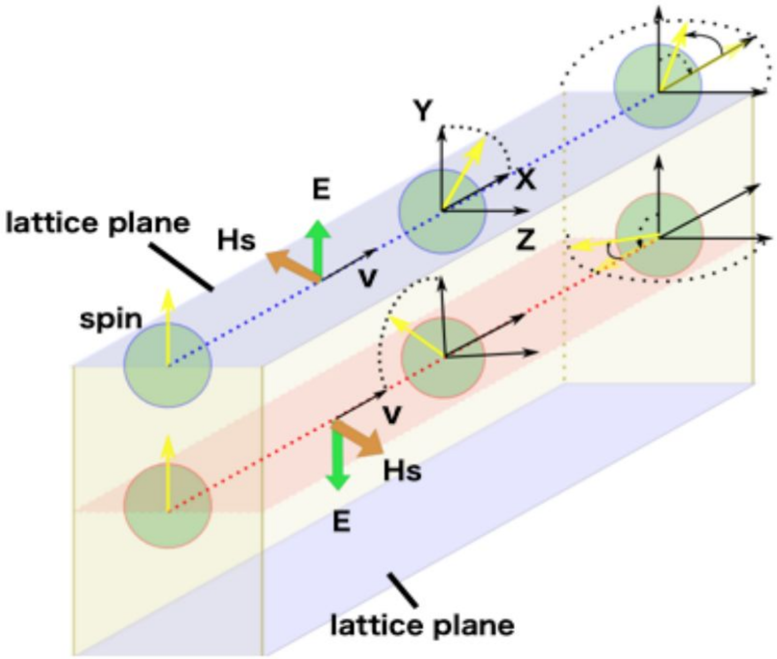

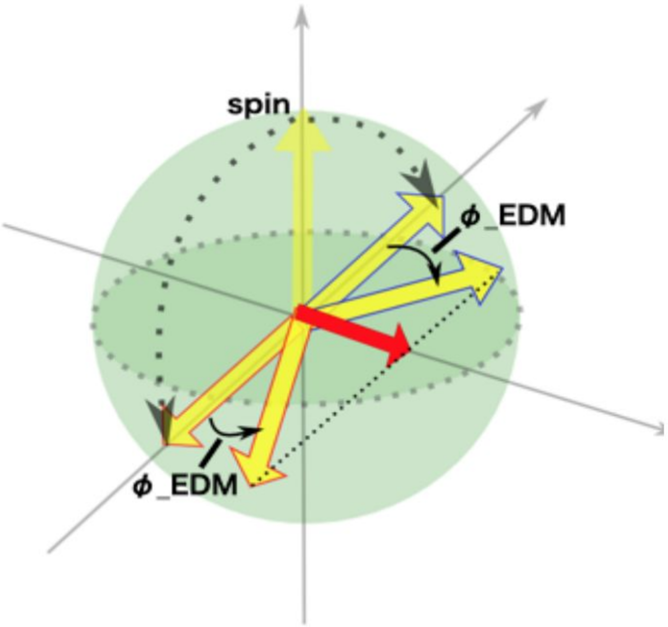

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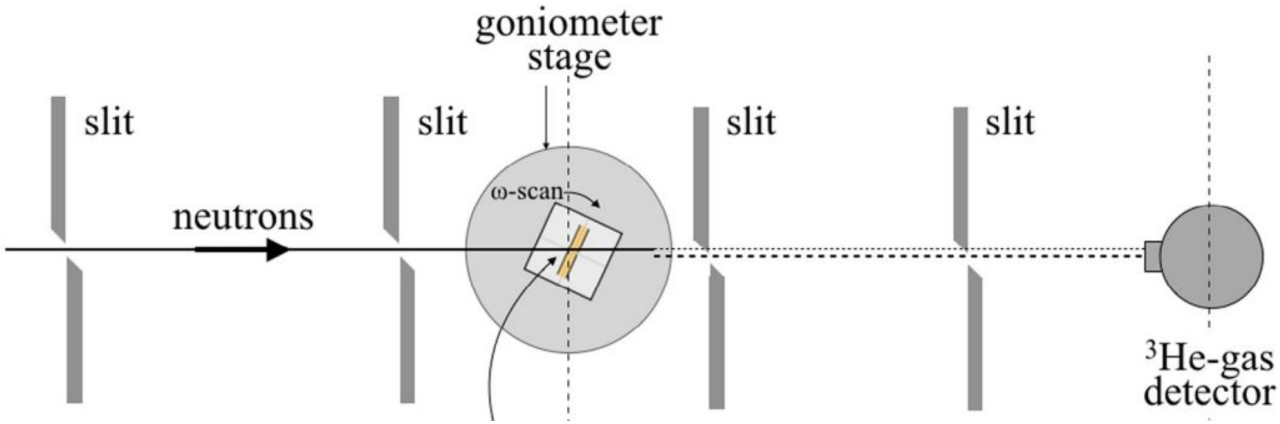
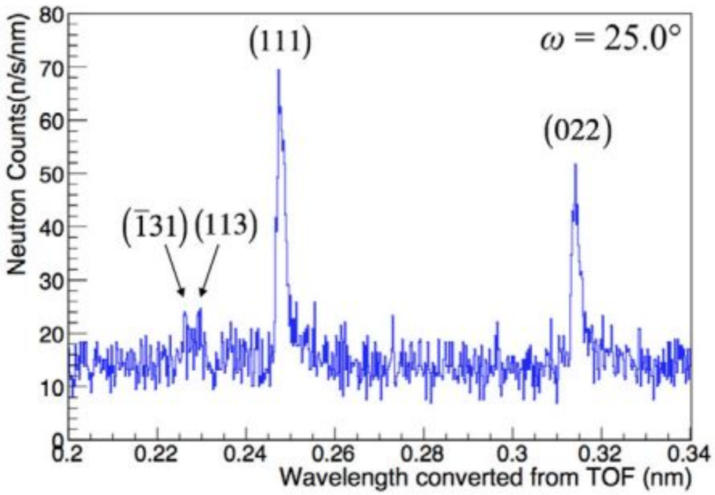
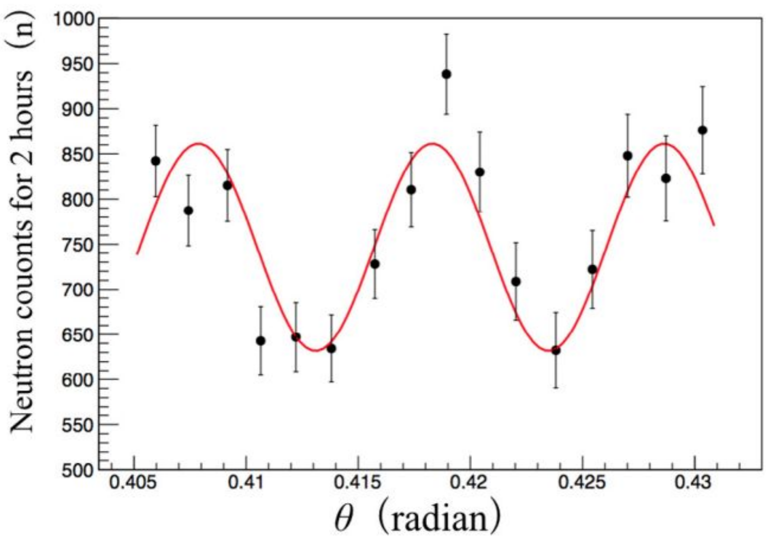
Pendellosung at a Pulsed Source!







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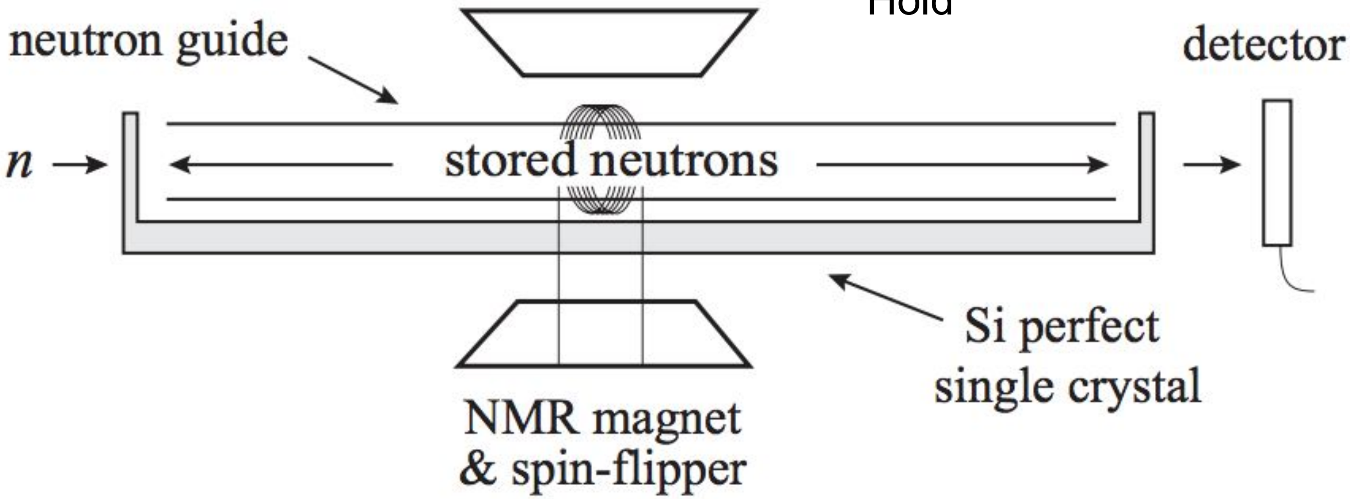
Resonators - Precedent

$T_{Hold} = 4$ s



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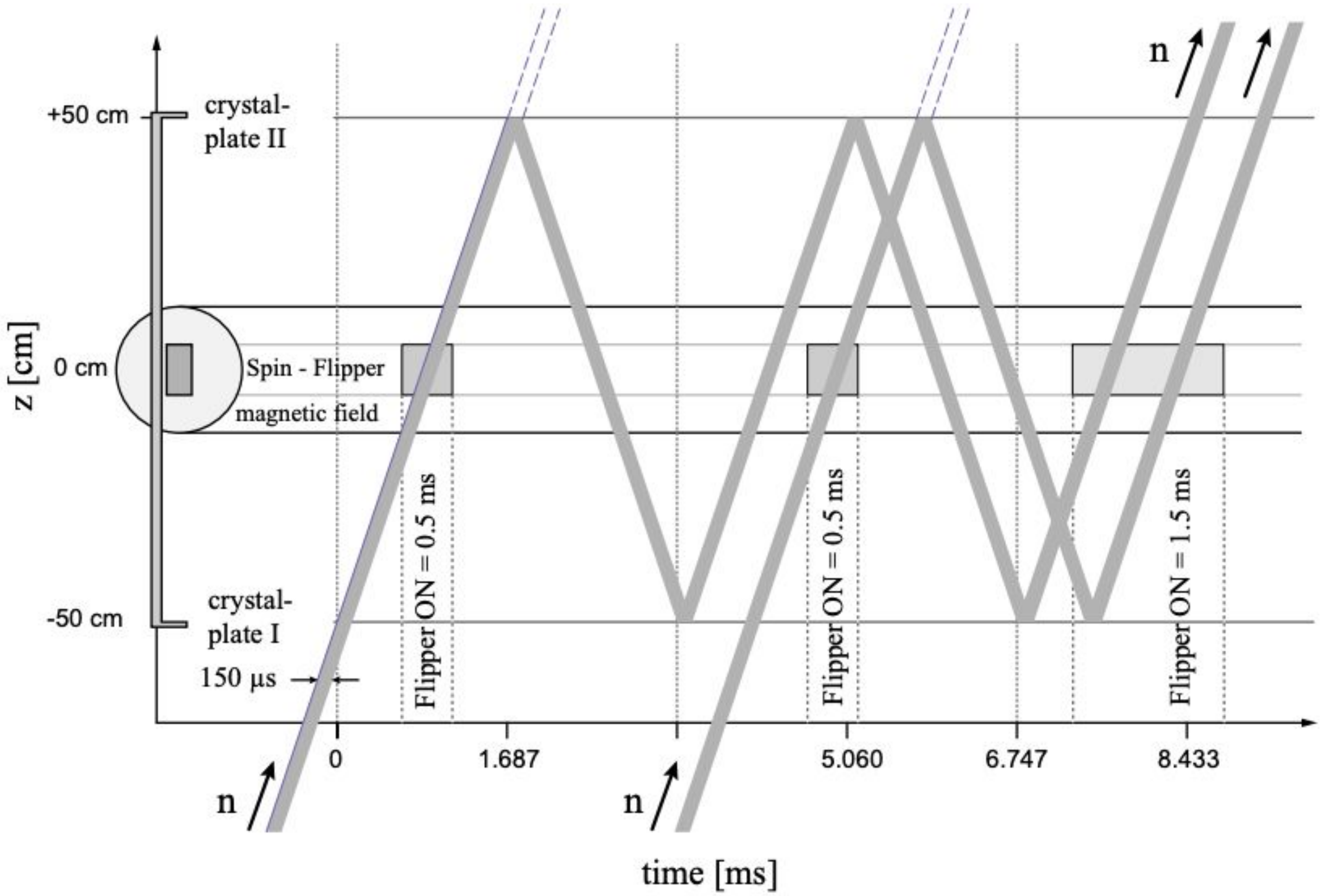

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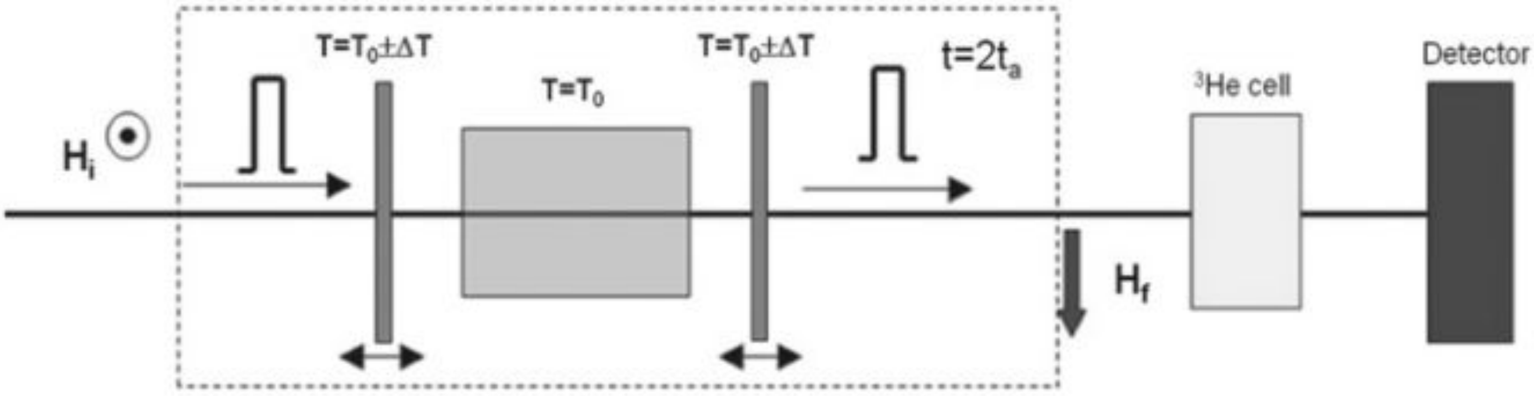
Resonators - Quartz



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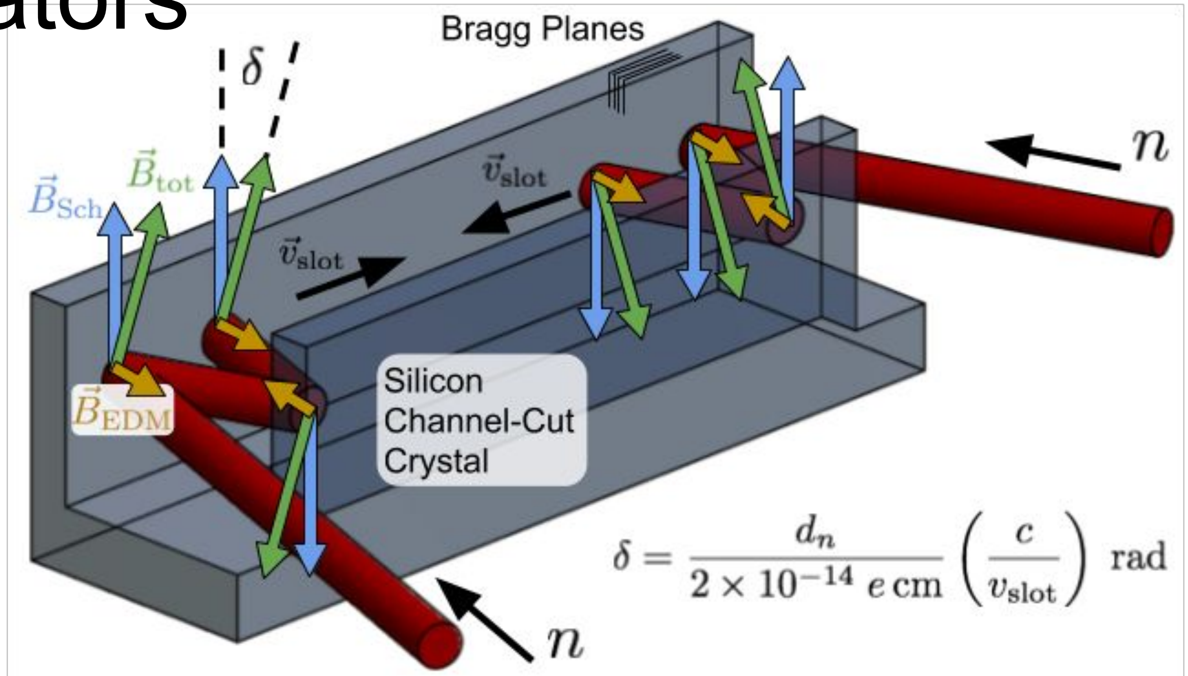
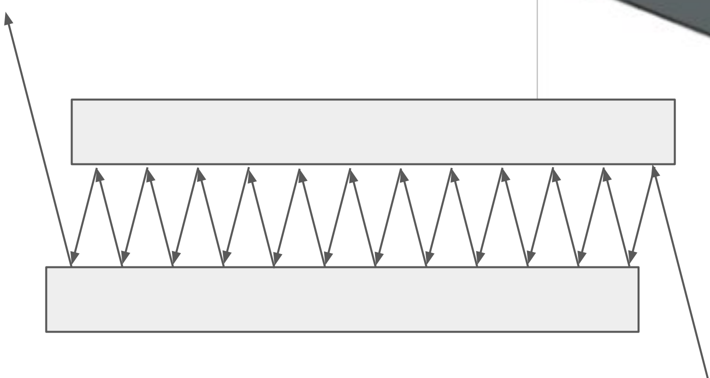
Si Resonators



$$R \propto \sqrt{\frac{v_H}{v_{-H}}}$$



$$|\psi_f\rangle = \left(1 + i \frac{b_{\mathrm{Sch}}}{b_N} \left(\hat{P} \times \hat{H} \right) \cdot \vec{\sigma} + i \frac{b_{EDM}}{b_N} \hat{H} \cdot \vec{\sigma} \right)^N |\psi_i\rangle$$

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Summary

Dynamical diffraction can probe time-violating effects by looking for spin rotation along the reciprocal lattice vector

Visibility of spin transport <u>inside</u> a crystal requires a noncentrosymmetric unit cell

Controlling for Schwinger scattering is both a major challenge and a control

Pulsed sources and resonators show promise for improving current crystal limits by over three orders of magnitude

Thank You!

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References

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